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GEOLOGIC FRAMEWORK OF THE CLARNO UNIT, JOHN DAY FOSSIL BEDS NATIONAL MONUMENT, CENTRAL OREGON

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ABSTRACT

Two major geologic events are recorded in the Eocene-Oligocene volcaniclastic strata, volcanic flows, and paleosols of the Clarno Unit of the John Day Fossil Beds National Monument. A major plate tectonic reorganization in the Pacific Northwest at about 40-42 Ma shifted volcanism from the Clarno volcanic province, represented by Clarno Formation andesitic flows and debris flows, to the Cascade arc, represented by John Day Formation tuffaceous deposits and ash-flow tuffs. Evidence of the second major geologic event comes from paleosols and fossil remains of plants and animals in these two formations which indicate a global paleoclimate change centered around the 34 Ma Eocene-Oligocene boundary when the earth changed from a tropical Eocene "hothouse" to a temperate Oligocene "icehouse."

In the Clarno Unit area, the lower part of the Clarno Formation consists of structurally domed debris flow conglomerates, andesite flows (51.2 ± 0.5 Ma), and a dacite dome (53.5 ± 0.3 Ma), both onlapped by less deformed debris flow conglomerates, andesite flows (43.4 ± 0.4 Ma) and red beds. The onlapping conglomerates are composed of two widespread units that are dominated by debris flows, separated by red claystones (paleosols), and are each approximately 60 m thick. The lower unit, conglomerate of the "Palisades," consists of channel and floodplain debris-flow conglomerates and lahar runout deposits. The overlying conglomerate of "Hancock Canyon" also contain channel and floodplain debris-flow conglomerates, but have in addition, fluvially reworked conglomerates and pebbly sandstones, reworked tuff beds, a distinctive amygdaloidal basalt flow (43.8 ± 0.5 Ma) and the "Nut Beds" fossil site. Both units accumulated on a floodplain between volcanic centers in response to volcanism (synvolcanic sedimentation) in an area of irregular topography, including hills of a pre-existing dacite dome.

Above the conglomerates are thick but discontinuous red claystones (claystone of "Red Hill"), which record a long period of local volcanic quiescence, slow floodplain aggradation, and long periods of soil formation. An abrupt climate change is inferred during accumulation of the red beds because the lower sequence contains Ultisol-like paleosols, whereas the upper sequence is Alfisol-like paleosols. The Ultisol-like paleosols and fossil plants from the "Nut Beds", which directly underlie the red beds, are evidence of a climate that was subtropical and humid. The abrupt transition to Alfisols in the uppermost Clarno red beds may represent a decline in both temperature and rainfall to cooler subtropical climate and correlates to a 42-43 Ma global paleoclimatic cooling event during the late Eocene. Disconformably overlying the red beds are gray-brown siltstones and conglomerates of the "Hancock Quarry" which have yielded a titanothere-dominated fossil fauna (Duchesnean North American Land Mammal Age).

The Clarno Formation is overlain abruptly by an ash-flow tuff of the basal John Day Formation, recently dated by single-crystal $^{40}Ar/^{39}Ar$ techniques at 39.2±0.03 Ma. A major lithologic boundary occurs in the lower John Day Formation between kaolinite and iron-rich claystones (paleosols) of the late Eocene, lower Big Basin Member, and smectite and tuffaceous claystones of the early Oligocene middle Big Basin Member. An age determination of 38.2 ± 0.07 Ma for a tuff in the lower Big Basin Member and a 33.6 ± 0.19 Ma age determination for the "Slanting Leaf Beds" in the middle Big basin Member, support the interpretation that the boundary between these two members is close to the Eocene-Oligocene boundary. These fossil leaf beds are thus earliest Oligocene in age, similar in age to the type locality of the Bridge Creek flora in the Painted Hills area.

INTRODUCTION

The scenic high desert of north-central Oregon contains a colorful volcanic and alluvial sequence of Tertiary age (Fig. 1). Three units of the John Day Fossil Beds National Monument (Sheep Rock, Clarno, and Painted Hills) were established for the protection and appreciation of the geologic and paleontologic resources in this area. Strata exposed in the National Monument record two important geologic events: (1) The change from Eocene Clarno arc volcanism, represented by the Clarno Formation, to late Eocene Cascade arc volcanism and John Day Formation backarc deposition is recorded in these two formations. (2) A dramatic paleoclimatic change occurred across the Eocene-Oligocene transition during which conditions changed in central Oregon from subtropical humid to semi-arid temperate climate. The magnitude and timing of these paleoclimatic changes as well as the stratigraphic position and age of fossil sites has been worked out from detailed mapping and section-measuring in the Clarno Unit area of paleosols (ancient soils), fossiliferous beds, and radiometrically dated tuff beds. This mapping has also revealed a domal volcanic edifice of Clarno age that was emplaced early in the accumulation of the formation and which was subsequently onlapped by volcaniclastic deposits.

The purpose of this paper is to provide a geologic and paleoenvironmental summary of the Clarno and lower John Day Formations in the Clarno Unit area of the John Day Fossil Beds National Monument. This paper represents a synthesis of the combined efforts of three different groups that have worked extensively in the Clarno area. A three year study by Bestland and Retallack for the National Park Service generated an extensive and detailed data base of mapping, volcanic and paleosol stratigraphy, new $^{40}Ar/^{39}Ar$ age determinations, and discovery of new fossil sites (Bestland and Retallack, 1994a). The University of Oregon Field Camp has been mapping in this area since 1985 and is developing a regional map of the Clarno and John Day Formations along the north side of the Blue Mountains uplift. Portland State University Geologic Field Methods students and staff have been mapping in this area since 1988 and have concentrated on detailed lithostratigraphic mapping of the National Monument.

During the study by Bestland and Retallack, special emphasis was placed on stratigraphic and chronostratigraphic ordering of Clarno fossil sites (Fig. 2). Detailed stratigraphic work focused on the upper part of the Clarno Formation in the interval containing the "Nut Beds" and "Hancock Quarry" fossil sites. Stratigraphic data presented in this report were gathered largely by measuring and describing stratigraphic sections of outcrops, with extensive trenching to exposed fresh rock beneath badlands mantled with soil, and mapping of units using low elevation color aerial photographs (Fig. 3). New age determinations combined with local lithostratigraphic mapping facilitated correlation of fossil sites in the Clarno Formation with the North American and world-wide paleontologic and paleoclimatologic data base. The study of the paleosols in the area was also a major focus of this project and is presented in two technical reports for the National Park Service (Bestland and Retallack, 1994a, b). Most of the paleoenvironmental conclusions presented in this paper are gleaned from this study.

The informal stratigraphic subdivisions of the Clarno and John Day Formations presented here are based on rock type and stratigraphic position. New stratigraphic units identified are all *informal* in accordance with rules about such units in the North American Commission on Stratigraphic Nomenclature (1983). The new subdivisions will be denoted by lower case such as "lower Big Basin Member."

GEOLOGIC SETTING

Clarno Formation

The Clarno Formation is a thick section (up to 6,000 ft./1800 m) of largely andesitic volcanic and volcaniclastic rocks of Eocene age which crops out over a large area of north-central Oregon. The formation was named by Merriam (1901a, b) for exposures of volcanic rocks at Clarno's ferry, now a bridge over the John Day River west of the National Monument boundary. The Clarno Formation overlies disconformably pre-Tertiary rocks that include highly deformed metasediments of Permian to Triassic age (Hotz and others, 1977), Cretaceous marine rocks in the Mitchell area and sedimentary rocks of uncertain age mapped as Cretaceous sedimentary rocks by Swanson (1969) and interpreted as Paleocene or Eocene sedimentary equivalents of the Herren Formation (Fisk and Fritts, 1987; Wareham, 1986). The formation is overlain for the most part by the John Day Formation. Where the formation formed ancient volcanic highlands, younger rock units such as the Miocene Columbia River Basalt Group, Miocene Mascall Formation, Miocene-Pliocene Rattlesnake Formation and the Miocene-Pliocene Deschutes Formation, disconformably overlie the Clarno Formation.

The Clarno Formation consists of non-marine volcanic and volcaniclastic units that range in age from middle to late Eocene, some 54 to 39 m.y. old (Evernden and others, 1964; Evernden and James, 1964; McKee, 1970; Enlows and Parker, 1972; Rogers and Novitsky-Evan, 1977; Manchester, 1981; Fiebelkorn and others, 1982; Vance, 1988; Walker and Robinson, 1990; Bestland and others, 1997; Manchester, 1990, 1994). Volcanic plugs, lava flows, and lahars, with convergent-margin andesitic compositions and textures, indicate accumulation in and around andesitic volcanic cones (Taylor, 1960; Noblett, 1981; Suayah and Rogers, 1991; White and Robinson, 1992; Bestland and others, 1995). The calc-alkaline volcanic rocks represent subduction-related andesitic volcanism, probably on thin continental crust (Noblett, 1981; Rogers and Novitsky-Evans, 1977; Rogers and Ragland, 1980; Suayah and Rogers, 1991). White and Robinson (1992) evaluated the sedimentology of the volcaniclastic deposits on a regional scale and interpreted the strata as non-marine volcanogenic deposits that were deposited in alluvial aprons and braidplains that flanked active volcanoes.

A variety of paleosols are present in the Clarno Formation: clayey alluvial paleosols of stable floodplains, weakly developed paleosols between debris flow deposits and andesite lava flows, and strongly developed residual paleosols with thick saprolite zones between major lithostratigraphic units (Table 1). Thick, residual paleosols have been previously recognized in several areas of the Clarno Formation and referred to variously as "soil zones," "saprolite," "weathering zones," and "laterites" (Waters and others, 1951; Peck, 1964; Hay, 1963; Fisher, 1964, 1968; Bestland and others, 1996). Some relatively continuous paleosol horizons have been used locally as marker horizons (Waters and others, 1951; Oles and Enlows, 1971); however, no regional stratigraphic framework utilizing volcanic marker beds or paleosol horizons has been attempted for the Clarno Formation (Oles and Enlows, 1971; Walker and Robinson, 1990). Red, clayey paleosols and thick saprolites are present throughout the

Clarno Formation, but, thick and laterally continuous exposures of these weathering profiles are most common in the upper part of the formation.

John Day Formation

The John Day Formation consists of rhyolitic ash-flow tuff and dacitic to rhyodacitic tuffs and alluvial deposits of latest Eocene, Oligocene, and early Miocene (39-to 18-my) age (Woodburne and Robinson, 1977; Robinson and others, 1990; Bestland and others, 1997, Bestland, 1997). Robinson and others (1984) interpret these primary pyroclastic, alluvial and lacustrine deposits as the distal deposits from vents to the west in the Western Cascades and from more proximal vents now buried or partially buried by the High Cascade volcanic cover. Thus, the transition between the Clarno and John Day formations record a late Eocene westward jump of the subduction zone in the Pacific Northwest and a corresponding change from Clarno andesitic volcanism to Cascade volcanism and John Day back-arc basin deposition.

The John Day Formation is divided into an eastern, western, and southern facies on the basis of geography and lithology (Woodburne and Robinson, 1977; Robinson and others, 1984). The Blue Mountains uplift separates the western and eastern facies and restricted deposition of much of the coarser-grained pyroclastic material to the western facies. The western facies is informally divided into members A through I based on laterally extensive of ash-flow tuffs sheets (Peck, 1964; Swanson and Robinson, 1968; Swanson, 1969). The western facies contains coarse-grained volcaniclastic deposits, welded ash-flow tuff sheets, and a variety of lava flow units including trachyandesite flows of member B, rhyolite flows of member C, and alkaline basalts in member F. The Clarno Unit area is in the western facies where the John Day Formation has been mapped in reconnaissance style by Robinson (1975) using the A through I stratigraphic divisions. The eastern facies is divided into four formal members (Fisher and Rensberger, 1972). From bottom to top they are, Big Basin Member (red claystones), Turtle Cove Member (green and buff tuffaceous claystones), Kimberly Member (massive tuff beds) and Haystack Valley Member (tuffaceous conglomerates). We report stratigraphic subdivisions of the John Day Formation in the Clarno Unit area based on both the A through I system of Peck (1964) and the formal members of the eastern facies of Fisher and Rensberger (1972) as modified by Bestland and others (1997) and Retallack and others (1996).

Paleosols have been described from the John Day Formation since Fisher (1964, 1968) recognized an iron, kaolinite-rich hardpan (laterite) between the Clarno and John Day formations (Table 1). Fisher (1968) also compared less well developed red and drab colored paleosols from the John Day Formation and noted their landscape association (well-drained with red colors and poorly-drained with drab colors) and their incipient lateritic character. Hay (1963) similarly recognized in these tuffaceous claystones evidence for "preburial weathering at the land surface." Both Hay (1962) and Fisher (1968) recognized distinct sedimentary facies in the John Day Formation, and inferred from these that hilly initial relief on the underlying Clarno Formation was mantled and subdued as deposition continued. Retallack (1981) noted correspondence of different paleosols in the Clarno Formation with former vegetation type. Getahun and Retallack (1991) identified an Alfisol-like paleosol in the red basal claystones of the formation in the Clarno Unit area. Retallack (1991a, b) interpreted the change in paleosol types of the John Day Formation from red clayey paleosols in the basal part to vitric calcareous paleosols in the upper part of the formation as indications of pronounced drying and cooling climatic conditions during late Eocene through Oligocene time.

Physiography

In the John Day River canyonlands of northcentral Oregon, each of the three major geologic divisions have a distinctive geomorphic expression (Fig. 4): (1) Resistant andesite and debris flow units of the Clarno Formation form dissected hilly canyonlands that are largely covered by thin soils. (2) The much finer-grained and less volcanically dominated John Day Formation, forms broad benches that are commonly covered by coarse colluvium and landslide debris originating from more resistant units upslope. (3) Capping many of the canyons with impressive cliffs are the resistant Columbia River Basalt Group. Another prominent feature in this area is the thick and resistant welded tuff of member A of the basal John Day Formation which forms a cuesta that can be traced throughout much of the area. The John Day Formation above this marker bed can be divided into a lower and upper part on the basis of geomorphic expression. The lower part consists of clayey and kaolinite-rich strata of the lower Big Basin Member which weather to form a gently-sloping bench covered with thick clayey soil. The Oligocene and Miocene parts of the John Day Formation contains tuffaceous strata rich in smectite clay and weather into steep badlands and sloping hills.

The erosional history of the area to its present day topography began in the late Miocene after cessation of Columbia River Basalt Group volcanism and deposition of the mid-Miocene Mascall Formation. A major tectonic break occurs in north-central Oregon between the Mascall Formation, dominated by fine-grained alluvium, and the disconformably overlying late Miocene Rattlesnake Formation, dominated by fanglomerates of basaltic composition. Thus, faulting and uplift of central Oregon must have begun sometime in the late Miocene.

In the Clarno area, landslides consisting of large and seemingly coherent blocks of basalt from the John Day Formation and Columbia River Basalt Group have slid over clayey soils confusing some of the distribution of basalt units. Pediment surfaces and colluvial soils dominated by basaltic fragments veneer much of the landscape. Small alluvial fans and dissected fanglomerate deposits of Quaternary age occur proximal to small canyons draining steep terrain of the Columbia River Basalt Group. Most of these deposits overly the John Day Formation. The fanglomerates contain caliche-cemented paleosols.

Clarno Formation Lithostratigraphic Units (Clarno Area)

In the Clarno Unit area, the Clarno Formation contains laterally extensive and mappable lithostratigraphic units (Figs. 2 and 3). These units are of three types: 1) andesitic debris flow packages, 2) andesite lava flows, and 3) claystones. Smaller-scale lithostratigraphic units, such as basalt flows or thin andesite flows, tuff beds and minor red beds were used to characterize and help identify larger stratigraphic packages. Of the three lithostratigraphic types, the debris and andesite flow units constitute the majority of the cliffs along the John Day River in the area south of Clarno bridge and along the western part of Pine Creek.

Lower Clarno Formation (Unit Tcl) A small window of older debris flows underlie the main Clarno Formation sequence in the Clarno Unit area (Fig. 3). These debris flows consist of a sequence of boulder-sized, matrix-supported conglomerates that are exposed just to the west of Hancock Canyon and are referred to as lower Clarno conglomerate. These debris flow deposits are of uncertain affinity and of local extent and were recognized by Hanson (1973, 1995) in a structural dome or anticline west of Hancock Field Station (Fig. 3). The anticline is a structural window into lower Clarno Formation strata that has been onlapped by later Clarno Formation deposits. The stratigraphic position and relationship of the deposits with the dacite body is not clear, however. The anticline plunges away from the dacite dome (Fig. 3), but a careful search of the deposits on the south side of the dacite dome failed to reveal a clear intrusive relationship. Clasts of boulders and cobbles of altered plagioclase porphyritic andesite are common in the debris flows. The unit lacks tuff beds or paleosols which could aid in stratigraphic correlation. The southwestern half of the structural dome is defined by the strike and dip of a resistant debris flow bed that is extensively exposed in this unit. The andesite of Pine Creek apparently overlies these folded debris flows, however, a small and poorly exposed outcrop west of the access road to Hancock Field Station and to the west along the north side of Highway 218 (NE⁄ sec 34) is the only exposure of this contact. Another less likely stratigraphic interpretation is that this unit is part of the conglomerate of the "Palisades" which have been locally faulted and folded. Our current interpretation is that there is a lower sequence of strata that was deformed by the emplacement of the dacite dome and that these deposits were onlapped by the main section of Clarno Formation units. Mapping by the University of Oregon group (Kays and Stimac) beginning in the early 1990's and continuing today reveals the presence of an extensive sequence of rhyodacitc tuffs and disrupted domes and dome flows on the western part of the Big Muddy Ranch area. Stratigraphic work in this area indicates that these tuffs and flows are lower than the ~51 Ma andesite of Pine Creek and could be equivalent to the "lower Clarno Formation" (see Fig. 2). Mapping by the University of Oregon group (Kays and Stimac), beginning in the early 1990's and continuing to the present, has revealed an extensive sequence of rhyodacitic tuffs and disrupted domes and dome-flows on the western part of Big Muddy Ranch. Stratigraphic work by this group indicates that these tuffs and flows are lower than the ~48 Ma andesites of Pine Creek.

Hancock Dacite Dome (Unit Tcd) A plagioclase-hornblende dacite porphyry is exposed in the hills and gullies to the northeast of Hancock Field Station (Figs 3, unit Tcd). The dome shaped rock body is pervasively altered and in the northern part of its outcrop extent consists of compact breccia. Massive, non-brecciated dacite is exposed in the bottom of gullies from which a sample was dated at 53.6 ± 0.3 Ma by R. Duncan (unpub. data). This igneous body was recognized by Hanson (1973) as an andesitic intrusion. Stratigraphic sections of strata directly overlying this igneous body do not show intrusive features such as baking, veining, hydrothermal alteration and mineralization (Bestland and Retallack, 1994a). The overlying claystones contain boulders exclusively of weathered, altered hornblende dacite (Fig. 5). The claystones are interpreted as well developed paleosols of the Pswa pedotype (Table 1; pedotypes described in Bestland and Retallack, 1994a) that developed on an igneous body and which incorporated colluvial debris (dacite clasts) from the underlying dacite (Fig. 5). Thus, the dacite body was an erosional feature that was mantled by colluvium and soils. The lack of intrusive igneous features in onlapping conglomerate of the "Palisades" and "Hancock Canyon" and the presence of cobbles and boulders of the dacite in colluvium suggests that the dacite was a topographic feature, probably a stubby lava flow or a lava dome. Strata directly south of the dome are the most deformed in the area (Fig. 3), dipping as steeply as 45°, and extensively fractured. Either the dome disrupted the strata during its emplacement and was not sufficiently hot to metamorphose the adjacent strata, or the strata were deformed against the rigid dome during later folding.

Andesite of Pine Creek (Unit Tcap) The base of the stratigraphically coherent section in the Clarno Unit area is a thick andesite flow referred to as the andesite of Pine Creek (Fig. 6a). The lava flows consist of dark-colored pyroxene-plagioclase andesite and a sample from the west lobe was dated at 48.4 ± 0.5 Ma (R. Duncan unpublished data). West of the "Palisades" a single, greater than 50 m thick flow, occurs in two lobes, judging by their similar lithologies and chemical composition (Table 3). These lobes terminate along the north side of highway 218 and extend northward no more than 600 meters into the Clarno Unit. Ramping (uniform joint planes dipping southeast due to flowing lava) in the west lobe suggests that the lava flow flowed to the northwest. The stratigraphic unit reappears at the ground surface near the picnic area at the mouth of "Indian Canyon" and crops out extensively east along Pine Creek. The andesite flows have a very irregular upper surface which consists of breccia mantled by a weathered red saprolite.

Paleorelief of this unit is best exposed in cliffs along Pine Creek between the "Palisades" cliffs and the entrance to

Hancock Field Station where more than 40 m of andesite is onlapped by debris flows over a lateral distance of 200 m. Pockets of red and white claystones (paleosols) are preserved between the andesite and overlying debris flows and were mapped separately (Bestland and Retallack, 1994a). The claystones are best exposed in roadcuts just east of the "Palisades" wayside on Highway 218. The clayey saprolite and claystones erode to form an erosional bench which is occupied in part by the modern Pine Creek floodplain. Basal sapping of these cliffs is in part due to the erodability of these claystones.

Conglomerate of the "Palisades" (Unit Tccp) Onlapping the irregular surface of the andesite of Pine Creek is a thick (55 m) sequence of debris flows dominated by clasts of andesitic composition (Fig. 6b, c). The conglomerate of the "Palisades" weather to form the spectacular hoodoos along Pine Creek (Fig. 7a) and in the lower part of the "West Face Cliffs" along the John Day River (Figs. 6a-c). Most of the conglomerates are matrix-supported, moderately clast-rich, laterally continuous and interpreted as floodplain debris-flows (in the sense of Scott, 1988). The "Palisade" cliffs contain numerous clast-rich, channelized debris flows. Some are clast supported at their base. Hyperconcentrated flood flow deposits (in the sense of G.A. Smith, 1986; and Nemec and Muszynski, 1982) are common at the base of debris flows where they grade into debris-flow deposits. Well exposed at approximately the middle of this unit, are several thin, green, clayey paleosols with wood fragments and leaf impressions. These thin, green paleosols, of the Scat and Sitaxs pedotypes (Table 1; Bestland and Retallack, 1994a), are present in the "Palisades" section and are well exposed in the lower part of the cliffs along the John Day River (Fig. 6c). Above the green clayey horizons is a tuffaceous breccia layer which grades upward into a massive debris flow. This debris flow weathers brown-orange and crops out prominently along the "West Face Cliffs."

To the east of Cove Creek, conglomerate of the "Palisades" onlap, thin and pinch-out against andesite of Pine Creek. From the "Palisades" cliffs to exposures in canyons on the north side of Horse Mountain, this lahar package has a dip of approximately 2^{o} toward the northwest, possibly dipping away from former volcanic highlands to the southeast. This dip is interpreted as an original debris flow apron gradient descending from a source area to the southeast.

Mantling the conglomerates of the "Palisades" is a saprolite horizon that is overlain by brown and red claystones (paleosols) all part of the conglomerates of the Palisades. These claystones erode to form a bench on the mesa between "Hancock Canyon" and "Indian Canyon." This bench is also present on the north and west sides of Horse Mountain and along the canyon walls of Cove Creek. These fine-grained deposits and claystones weather to form low-angle slopes and reddish soil and were mapped separately by Bestland and Retallack (1994a). They are well exposed in the south spurs of the first upstream westward branching gully of both "Indian Canyon" and Cove Creek.

Andesite of "West Face Cliffs" (Unit Tcawf) This thick andesite is locally present in the southern part of the project area south of Clarno along the John Day River (Fig. 6a). Here the unit is exposed in the lower half of the monolithic buttes on the west side of the river (hills 2441 and 2373, sec 9) and consists of blocky, dark-colored, pyroxene-plagioclase andesite. At the base of hill 2441 along the John Day River, the unit fills a paleovalley cut into the conglomerates of the "Palisades." In the "West Face Cliffs", the unit is clearly onlapped by conglomerate of Hancock Canyon."

Conglomerate of Hancock Canyon (Unit Tcch) Overlying both the red claystone beds at the top of the conglomerate of the "Palisades" and the andesite of "West Face Cliffs" is the conglomerate of "Hancock Canyon" (Fig. 7a). Like the conglomerate of the "Palisades," clasts in this unit are principally of andesitic composition. A nearby volcanic source is also indicated by heavy minerals of the "Nut Beds" which are mainly of volcanic affinities (77% magnetite/ilmenite, 2% zircon, 4% pyroxene and 2% rutile) with less than 2% possible metamorphic minerals (garnet, epidote, amphibole; M. Sorenson, pers. comm., 1983). This unit includes tuffaceous beds and a distinctive basalt flow, but is dominated by matrix-supported boulder debris flows. Deposits of this unit onlap the Hancock dacite dome and the middle Clarno andesite unit. In the Clarno Unit area, the conglomerate of Hancock Canyon can be distinguished from the conglomerate of the "Palisades" by their more prominent bedding, less coarse-grained and massive texture, and common thin tuff interbeds (Fig. 7b).

The conglomerate of Hancock Canyon contains the "Nut Beds" fossil site, a 7 m thick by 300 m wide lens of silica-cemented sandstone and conglomerate, with prolific floral remains. Radiometric age determinations on the "Nut Beds" and the Muddy Ranch tuff, are approximately 44 Ma; Carl Swisher obtained a date of 44 Ma from a plagioclase separate from a reworked crystal tuff in the "Nut Beds" using the ^{40}Ar/^{39}Ar method (pers. comm., 1992), and Brent Turrin (for Manchester 1990, 1994) used the same method on plagioclase of the "Nut Beds" for an age of 43.76±0.29 Ma. J. Vance (1988) obtained dates of 43.6 and 43.7 Ma from fission track of zircon crystals in the 'Nut Beds" and 44 Ma in the Muddy Ranch tuff (also known as the Rajneesh Tuff) near the Gable. The Muddy Ranch tuff is stratigraphically below the "Nut Beds." Many large, well-preserved *Cercidiphyllum* (katsura) and *Macginitea* (sycamore) permineralized tree trunks and limbs are in the conglomerates of Hancock Canyon.

Basalt of "Hancock Canyon" (Unit Tchb) A distinctive and widespread amygdaloidal basalt flow occurs stratigraphically in the upper half of the conglomerates of "Hancock Canyon." The basalt is holocrystalline, contains common plagioclase and pyroxene grains, displays pahoehoe flow structures, local columnar jointing, and has been dated at 43.8 ± 0.5 Ma by R. Duncan (unpub. data). The basalt can be mapped from the Hancock Field Station area to the Gable, is thickest (23 m) in the "West Face Cliffs," but is not present east of “Indian Canyon” (Fig. 3). This basalt flow can be traced along the cliffs of the John Day River south to Melendy Ridge, a distance of 14 km. The flow is very vesicular at its base, indicating that it flowed over moist terrain where heat from the lava vaporized the moisture, and the steam penetrated upward into the cooling yet still molten lava. Locally these gas holes are filled with agate, a form of silica precipitated from ground water.

Claystone of “Red Hill” (Unit Tcrh) In the Clarno Unit area, a thick sequence of reddish (Lakayx pedotype) and grayish-purple (Acas pedotype) claystones overlie the conglomerate of “Hancock Canyon” (Fig. 8a, b). The unit is 59 m thick in the “Red Hill” area (Fig. 2) but thins dramatically to the east. In the cliffs on the west and north side of Horse Mountain, only a reddish saprolite with thin clay layer is present at this stratigraphic level. The unit at “Red Hill” contains a lower reddish paleosol sequence of very deeply weathered Ultisol-like paleosols (Lakayx pedotype) and an upper less well developed, Alfisol-like paleosol sequence (Luca pedotype; G.S. Smith, 1988; Retallack, 1981). A stony tuff bed above the lowest Luca paleosol approximately divides the two paleosol sequences and has been dated at 42.7 ± 0.3 Ma by R. Duncan (unpub. data).

Conglomeratic beds are locally present in the claystones. At the southern tip of the Gable (Fig. 3), a thick (18 m), coarse-grained conglomerate body is interbedded with red claystones (Unit Tcrg). The conglomerates are clast-supported, contain rounded clasts of andesite and amygdaloidal basalt. The conglomerates cut into red claystones and underlying units of the conglomerate of “Hancock Canyon” (Fig. 8c).

The claystones of “Red Hill” are prone to landslides. Most landslides in the area occur where thick exposures of these claystones are overlain by the welded tuff of member A of the basal John Day Formation. Good examples of these landslides occur on the eastern side of “Indian Canyon.” The landslides do not appear deep seated; the coherent blocks of member A form shallow, rocky slides, which in some cases are similar in appearance to rock glaciers.

Andesite of Horse Mountain (Unit Tcah) This thick andesite unit is extensively exposed in the Clarno area where it caps much of Horse Mountain (Fig. 6a & b) and has been dated at 43.4 ± 0.4 Ma by R. Duncan (unpub. data). The unit consists of platy to blocky andesite which varies from pyroxene-plagioclase andesite to very porphyritic plagioclase dacite with traces of hornblende. Along the west and north side of Horse Mountain, the unit overlies a 2 m thick red saprolite developed on the amygdaloidal basalt flow (Unit Tchb) in the conglomerate of “Hancock Canyon” unit. Ramp-like flow structures are common in lava flows exposed in the “West Face Cliffs.” The base of the unit dips gently to the west, probably following a paleoslope.

An upper andesite unit (Tcau) is recognized within the andesite of Horse Mountain based on stratigraphic position and lithology. On the rolling top of the west part of Horse Mountain, a plagioclase phyric, basaltic andesite flow is exposed above a 1-3 m thick red claystone unit (paleosols) and below member A of the basal John Day Formation. This unit (Tcau) has been mapped and identified by bulk rock geochemistry (Bestland and Retallack, 1994a). Lithologically and geochemically similar andesite crops out in the upper part of Hancock Canyon where it underlies the siltstones of the “Mammal Quarry.” In badland exposures to the east of “Red Hill,” a saprolitized andesite breccia can be traced into coherent exposure of this upper andesite unit.

Siltstone of the “Hancock Quarry” (Tcmq) The tan, clayey siltstones and cobble conglomerates of the “Hancock Quarry” beds are only locally present in the “Red Hill”-Indian Canyon area. Vertebrate remains in this unit make it paleontologically important. A diverse vertebrate fauna has been excavated from the “Hancock Quarry,” located stratigraphically in the uppermost Clarno Formation and below member A of the John Day Formation (Hanson, 1973, 1989, 1995). Several taxa in this assemblage have close affinities with Asiatic faunas and the early Duchesnean North American Land Mammal Age. Pratt (1988) described Inceptisol-like paleosols from the “Hancock Quarry.” By her interpretation, the fossil remains accumulated as carcasses and were disarticulated in a fluvial point bar. At several exposures east of the “Hancock Quarry,” red claystones of the “Red Hill” claystone unit are overlain by andesite breccia that can be traced to outcrops of andesite of Horse Mountain (Fig. 3). This breccia is capped by a well developed paleosol which is overlain by the tan clayey siltstones of the “Mammal Quarry” unit. Thus, the upper andesite unit of the andesite of Horse Mountain (Tcau) may have contributed to the deposition of these beds by altering the landscape and drainage.

JOHN DAY FORMATION LITHOSTRATIGRAPHIC UNITS (CLARNO AREA)

In the Clarno Unit area, the John Day Formation has been mapped and stratigraphically subdivided by Robinson (1975) following Peck’s (1961, 1964) informal subdivision of the John Day Formation on the basis of distinctive pyroclastic and lava flow units. In this paper, these pyroclastic and lava flow units are recognized and given the names defined by Peck (1964) and mapped by Robinson (1975); however, only distinct lithologic units were mapped in the Clarno Unit area (Fig. 9). These volcanic units, along with the interbedded claystones, lacustrine shales and tuffs, are assigned to eastern facies members of the John Day Formation (Fisher and Rensberger, 1972).

lower Big Basin Member

The lower Big Basin member in the Clarno Unit area includes all lithostratigraphic units from and including the welded tuff of member A of the basal John Day Formation up to a truncation surface marked in places by conglomerates and sandstones of probable Oligocene age (Fig. 2). These sandstones and conglomerates are exposed in gullies to the west of the "Slanting Leaf Beds" which they are stratigraphically below.

Welded Tuff of Member A (Unit Tjat) Rhyolitic pyroclastic volcanism of the John Day Formation is first recorded in north central Oregon by an ash-flow tuff now re-dated in the Clarno area at 39.2 Ma and by a 39.7 Ma date from this tuff in the Painted Hills area by Carl Swisher (see Bestland and Retallack, 1994a, b, for age determination data). This basal ash-flow tuff sheet is extensively exposed in the western facies (Peck, 1964; Robinson, 1975). The distinctive and widespread ash flow tuff of member A is useful in delineating the Clarno surface at the onset of John Day volcanism (Fig. 10a).

A lower, densely welded tuff forms prominent outcrops in the Clarno Unit area and is approximately 30 m thick. A perlitic vitrophyre occurs locally at the base and is best exposed in roadcuts at the Gable. At the very base of the ash-flow tuff are unwelded tuff deposits some containing accretionary lapilli and plant remains (Fig. 10b). Lithic fragments are common in the lower tuff as are bi-pyramidal (beta) quartz crystals. The tuff, where densely welded, has a red-purple color.

An upper, weakly welded to unwelded part of the ash flow tuff, approximately 25 m thick, crops out extensively in the Clarno Unit area where it commonly forms the dip slope on the member A cuesta. This unit also contains abundant bi-pyramidal quartz crystals but less lithic fragments than the lower densely welded part. Fluvially reworked beds occur in places such as in upper "Indian Canyon" area where concentrations of bi-pyramidal quartz and feldspar crystals derived from the underlying tuff occur.

Member B Basaltic Andesite (Unit Tjba) In the Clarno Unit area, distinctive aphanitic basaltic andesite flows overlie member A. Red claystones are locally present between the two units, although exposure of this thin interbed is poor. The flows consist of aphanitic to sub-glassy basaltic andesite that weather into cobble-sized blocks. These basalts correlate with the member B trachyandesites of Peck (1964) which form a thick unit in the Ashwood area (Swanson, 1969), but have also been mapped in the Clarno Unit area (Robinson, 1975). Peck (1964) identified 460 m of very dark gray aphanitic flows of trachyandesite in the Ashwood area. These basaltic andesite flows of member B of the John Day Formation are widespread in the western facies (Peck, 1964; Robinson, 1975) and occur as flows and dikes in the Clarno Unit area. In the Clarno Unit area, a 21 m thick columnar jointed basaltic andesite lava flow crops out at the head of Indian Canyon and is the thickest occurrence of member B in the area. Other small exposures are scattered throughout the area and are recognizable by their aphanitic texture and small cobble-sized weathering character, similar to Peck's (1964) description of member B. A set of basaltic andesite intrusions of this lithology forms a small hill between Hancock Canyon and Indian Canyon (NE⁄of sec. 26). The rock contains pebble-sized cognate xenoliths of gabbro. The geochemistry of lava flows and dikes are very similar in composition (Bestland and Retallack, 1994a).

White Tuff of Member F (Unit Tjft) A massive white vitric tuff approximately 1-3 m thick is widespread but poorly exposed in the lower John Day Formation in the Clarno area. This white vitric tuff is low in the John Day Formation in the Clarno area and interbedded with clayey red beds of the lower Big Basin Member and has been referred to previously as the member F tuff. This vitric tuff was dated at the "White Knoll" locality at 38.2 Ma by C. Swisher (see Bestland and Retallack, 1994a). Getahun and Retallack (1991) identified an Alfisol-like paleosol (Luca pedotype) directly below this tuff at "Whitecap Knoll." Robinson and Brem (1981) identified a massive white vitric tuff located in a roadcut just west of Clarno Grange on Highway 218 as the base of member F in this area. However, recent $^{40}Ar/^{39}Ar$ age determinations on the member F tuff in its type area in the western facies indicate an early Oligocene age (pers. com. G.A. Smith, 1996; Smith and others, 1996). And, according to Peck (1964), the weakly welded ash flow tuff that defines the base of member F is not a widespread unit. Thus, the correlation of this tuff in the Clarno area with the western facies type area is not tenable with these recent dates.

lower Big Basin Member Claystones (Unit Tjlb) Widespread, thick clayey red beds in the lower part of the John Day Formation in the Clarno Unit are mapped as lower Big Basin Member based on lithologic and stratigraphic similarities with the type section of this member in the Big Basin area of Picture Gorge. Recently recognized subdivisions of this member in a reference section from the Painted Hills area (Bestland and others, 1996, 1997; Bestland and Retallack, 1994b) are also recognized in the Clarno Unit.

The John Day Formation in the Clarno Unit area contains a thick section of late Eocene strata, as indicated by the 38.2 Ma and 33.6 Ma age determinations of strata from this area. These late Eocene paleosols are not dominated by colluvial reworked and lateritic paleosols as are paleosols of this age in the Painted Hills and Big Basin areas (Bestland and others, 1994a, 1996; Bestland and Retallack, 1994b). The Clarno area part of the John Day basin was probably a floodplain depocenter during the late Eocene, rather than a colluvial slope as is indicated for areas to the south and east.

middle and upper Big Basin Members (Unit Tjmb)

The middle and upper Big Basin Members were not delineated in the Clarno area as they have been in the Painted Hills area (Bestland and Retallack, 1994b). In the Clarno area, red-brown silty claystones, tuffs, and lacustrine shales with leaf impressions, similar to strata in the Painted Hills area identified as middle Big Basin member, occur above clayey red beds identified as the lower Big Basin Member and below green tuffaceous strata of member G containing the sanidine tuff (Fig. 9). This tuff occurs in the lower part of the Turtle Cove Member in the Painted Hills where it was dated at 29.8 Ma. Additionally, the 33.6 Ma age determination from the "Slanting Leaf Beds" and the well documented Bridge Creek flora (Manchester and Meyer, 1987; Meyer and Manchester, 1994) from these strata allows correlation with the middle Big Basin Member. In the Painted Hills area age determinations on tuff beds of 33.0 Ma and 32.7 Ma (Bestland et al., 1997) are associated with the type locality of the Bridge Creek flora (Chaney 1924, 1948) and are contained within the middle Big Basin Member (Bestland, 1997). Red silty claystones stratigraphically above the "Slanting Leaf Beds" and below a cliff-forming channel complex (Fig. 10c) are similar to Ticam and Skwiskwi pedotypes identified in the middle and upper Big Basin members from the Painted Hills (Bestland and others, 1997 for pedotypes).

At the base of the middle Big Basin Member and locally present in the Clarno area, are conglomerates containing weathered clasts of tuff and igneous flow rocks (Fig. 2). In gullies to the west of the "Slanting Leaf Beds", brown calcareous paleosols overlie these conglomerates and underlie the lacustrine and carbonaceous shales of the "Slanting Leaf Beds." These conglomerates fill an incised surface cut into underlying claystones of the lower Big Basin Member and represent a major truncation surface, similar to a truncation surface identified in the Painted Hills area (Bestland and Retallack, 1994b). This truncation surface approximates the Eocene-Oligocene boundary.

Member F Basalts (Unit Tjfb) Alkaline olivine basalts of member F of the John Day Formation (Robinson, 1969) occur extensively in the Clarno area. Below Iron Mountain, John Day Formation basalts of member F are in contact with Columbia River Basalt Group. Lava Flows of this unit are also interbedded with tuffaceous deposits and paleosols of the middle and upper Big Basin Members. The stratigraphically lowest alkaline basalt is less than 10 m above the "Slanting Leaf Beds."

Turtle Cove Member

Tuffs and tuffaceous siltstones and claystones of the Turtle Cove Member are recognized in the Clarno Unit based on correlation of tuffs in the western facies with this member in the eastern facies (Woodburne and Robinson, 1977). Ash-flow tuffs of member G, H, and I occur in the Clarno Unit area. Member H has been correlated with the "Picture Gorge ignimbrite" based on lithology and stratigraphic position (Robinson and others, 1990). The Turtle Cove Member as well as the ash-flow tuffs of member G, H, I are exposed in The Cove, on the west side of Iron Mountain above the John Day River, and have been mapped previously by Robinson (1975) and by Bestland, Blackwell and Kays (unpublished mapping 1986 and 1988). These tuff units are significant in the context of correlating the Turtle Cove Member of the John Day Formation with the western facies of the John Day Formation.

Member G Tuff This ash-flow tuff sheet is extensively exposed in the western facies (Robinson, 1975) and along the Iron Mountain escarpment, and in The Cove in the Clarno area. This sanidine rich tuff has been correlated with a sanidine tuff in the Painted Hills area (Hay, 1963; Woodburne and Robinson, 1977) which has been recently dated at 29.8 ± 0.02 Ma (Bestland and others, 1997). In the Clarno area the tuff is 1-6 m thick, gray, yellow-gray and green-gray, non-welded to weakly welded, and contains abundant sanidine and quartz crystals in a vitric groundmass. A distinctive set of green and greenish-blue tuffaceous claystones and siliceous claystones occurs above the sanidine bearing tuff. Locally in The Cove, this section contains beds rich with snails.

Member H Tuff Above the greenish tuffaceous deposits is a thick (10-20 m), light brown, fine-grained welded ash-flow tuff sheet that is widespread in the western facies (Peck, 1964; Robinson, 1975) as well as in the eastern facies (Fisher, 1966a) where it is referred to as the "Picture Gorge ignimbrite." Two recent age determinations of this unit in the Painted Hills are both 28.7 ± 0.07 Ma (Bestland and others, 1997). This tuff is crystal poor and contains variable amounts of lithic fragments of rhyolite and tuff. Two cooling units are present in the Clarno area as has been recognized in the eastern facies by Fisher (1966a). To the west of Clarno, closer to the source, only one cooling unit is recognized (Robinson and others, 1990). In cliffs below the Columbia River Basalt Group on Iron Mountain, member H tuff is commonly overlain directly by the member I ash-flow tuff sheet with no intervening sedimentary deposits. Elsewhere in the western facies, tuffaceous sedimentary deposits occur between the tuffs of member H and I.

Member I Tuff In the Clarno area, this distinctive coarse-grained ash-flow sheet occurs in scattered exposures high on the slopes of Iron Mountain. It was eroded in most places prior to the accumulation of the Columbia River Basalt Group. The tuff is up to 15-20 m thick and contains coarse pumice fragments, coarse vitric shards, and obsidian fragments. Where the base of the unit is exposed, these pebble-sized obsidian fragments are vaguely cross-bedded and may represent the basal surge of the ash-flow.

STRUCTURE OF THE CLARNO UNIT AREA

Strata of the Clarno and John Day Formations, and overlying flows of the Columbia River Basalt Group are gently to moderately folded, forming broad, open generally northeast-plunging folds (Fig. 3). This orientation is parallel to the elongation of the Blue Mountains in northeastern Oregon. Faults, on the other hand, strike west to northwest, generally in a direction normal to fold axes. They commonly show right-lateral strike-slip movement with displacements less than a few hundred meters. Deformation was caused by a northwestward-directed compressive (shear) stress which folded the strata and moved fault-bounded Clarno blocks in the south westward relative to the northern blocks. Because dips of the strata decrease upward stratigraphically, deformation was underway during deposition of Clarno Formation, between 55-45 Ma, and continued past the outpouring of Columbia River Basalt Group at 16-15 Ma.

Folds

A series of subparallel, broad, open folds in the Clarno Unit and vicinity strike generally northeast, plunging about 3-5°. Fold limbs dip up to 45° in the intensely deformed strata of the lower Clarno conglomerates but dip no more than 30° in younger Clarno strata. Dips are 20° or less in John Day Formation strata. The steepest dips in the John Day Formation occur in member A welded tuff of the basal John Day Formation in the cuesta along the west side of the Clarno Unit. The tightest folding occurs in the Hancock anticline south of Hancock dome. Intrusion or eruption of the hornblende dacite probably domed the surrounding country rock producing this anticline. Later erosion, deposition and folding has masked much of this relationship. This older sequence is only found around the dacite dome and has not been correlated to other units in the area. The dip in strata of the folds to the east is less, making the folds there no more than undulations (see cross-sections in Fig. 3). To the southeast of the Hancock anticline the stratigraphic level rises topographically, indicating regional structural uplift to the southeast.

Faults

Detailed mapping in the Clarno area has revealed a number of small-displacement faults striking east-west to northwest. Faults are en echelon and progress northward from west to east, approximately following the trend of the large open fold (Fig. 3). Fault displacement is generally down on the south and show indications of strike-slip movement with displacement up to a few hundred meters. Strike-slip indicators include horizontal to oblique slickensides in silicified conglomeratic sandstone of the "Palisades" and Hancock Canyon units along the sides of Hancock Canyon and Indian Canyon. Vertical displacements here are less than 10 m. About 300-400 m of right-lateral displacement occurs on the west-northwest striking fault, that transects the Hancock anticline in the southern area of the Clarno Unit. A short, steeply dipping reverse fault, west of the Hancock Field Station, offsets the core of the Hancock anticline, bringing lower Clarno conglomerates into contact with beds of "Hancock Canyon."

Petrology

Geochemical analyses of rock units in a diverse terrain, such as the Clarno Unit and vicinity, considerably aids the field study by enabling correlation, establishing the stratigraphic order, and working out the structure. Major-and trace-element chemical analyses and modes of rock samples taken from selected units are summarized in Table 2. Petrographic descriptions of the samples are given in Table 3. Comparison of compositions listed in Table 2 and identified in Figures 11 and 12, show that several samples are similar chemically. In addition they are similar petrologically and occupy similar stratigraphic positions, and therefore, are probably correlative. They are (a) the clast of rhyodacite (sample #2) and dacite of Hancock dome (sample #1), (b) lobes of andesite of Pine Creek (samples #3 and 4), (c) two samples (#11 and #12) of tuff of Current Creek, and (d) the andesitic dike (sample #15) cutting conglomerate of "Hancock Canyon" and andesite lava flow in John Day Member B (sample #16).

Most lava flows in the Clarno Formation and John Day Formation are gray to dark colored, commonly phyric with moderately abundant plagioclase, hornblende and lesser amount of orthopyroxene; clinopyroxene, biotite, and quartz are rare. All tuffs are very light colored and contain moderate to sparse amounts of crystals, generally plagioclase, quartz, and sanidine, in order of decreasing abundance. Compared with volcanic units of the western Cascades, Clarno units are distinguished by their content of hornblende and lack of clinopyroxene. Tuffs in the Clarno and John Day formations commonly contain quartz and some sanidine, which has not been reported in Cascade tuffs.

Because Clarno volcanic units generally contain little pyroxene yet significant amount of hornblende and sodium-rich plagioclase, and are moderate to rich in SiO_2, K_2O, Na_2O and poor in MgO, they are products of considerable magmatic evolution and differentiation (Table 3; Figs. 11a and b). Most of these units are representative of the calc-alkaline series. They show a slight tendency toward FeO enrichment (Fig. 11b) in comparison with Cascade lavas (Carmichael, 1964). The trachybasalt lavas in the lower part of the John Day Formation (sample #17) appear to be alkalic (Fig. 11A). Tuffs (samples #13, 14, 18, 21, and 22 in Fig. 11A) contain relatively low amounts of Na_2O and K_2O and have likely undergone weathering and leaching.

Most Clarno Formation lava and tuff have low Nb contents typical of arc volcanic rocks, whereas John Day Formation lavas and tuffs, and the Clarno amygdaloidal lava flow (sample #6) have greater amounts of Nb, indicative of a possible mantle or subcrustal component in their origin (Fig. 12a and b). Most Clarno Formation units plot in the volcanic arc setting, whereas John Day Formation units plot within-plate setting (Fig. 12a).

SEDIMENTATION, VOLCANISM, AND PAST CLIMATE CHANGE

Clarno Formation Depositional Setting

The Clarno Formation sedimentary units in this area can be broadly grouped into coarse-grained debris flow dominated deposits and fine-grained, alluvial paleosol or overbank deposits. White and Robinson (1992) interpret the coarse-grained Clarno Formation deposits as proximal, nonmarine lahar aprons and reworked fluvial deposits that flanked stratovolcanoes, possibly in fault-bounded minibasins in a tensional arc setting, similar to the Quaternary High Cascade graben of the central Oregon Cascades (Taylor 1990, Smith and others, 1987). Fine-grained overbank deposits and paleosols are common in the formation, however due to the poor exposure of these claystone units, the distribution and sedimentology of these units has been largely ignored (Robinson, 1975; Swanson, 1969) except in a few places such as "Red Hill" (Retallack, 1981; 1991a) and in the Cherry Creek area where White and Robinson (1992) briefly describe a thick section of clayey red beds.

Debris Flow Features Debris flow and debris flow runout deposits are the most common coarse-grained deposit type in the Clarno Unit area. A common deposit sequence consists of a thin layer of vaguely bedded pebbly conglomerates at the base of massive debris flows such as occurs at the base of the lahar containing the "Hancock Tree." The vaguely bedded, granular or pebbly sandstones common in the Clarno Formation have grain to grain contact and stringers of coarser clasts indicating deposition by traction current. However, cross-bedding or climbing bedforms are missing, indicating that these are not normal fluvial deposits. Deposits such as these have been recognized as an intermediate between fluvial and debris flow processes and referred to as hyperconcentrated flood flow deposits (Smith 1986; Nemec and Muszynski, 1982).

Another common feature in the coarse-grained deposits of the Clarno Formation are clast-rich channelized debris flows. In the south facing part of the "Palisades" cliffs, clast-rich and clast-supported debris flows fill channels cut deeply into underlying lahars. The lahar layers and superposition or nesting of channels in this locality is complex. The resulting stratigraphy consists of laterally discontinuous layers on a scale of 10's of meters that contain protruding sticks and logs. Scott (1988) documents channel facies debris flows from the deposits of the 1980 Mt. St. Helens eruption. These channel facies debris flows are commonly clast supported, sit on an eroded pavement, are localized to the channel area, have protruding logs and sticks and have large-scale longitudinal bar features referred to by Scott (1988) as whale back bars.

In central Oregon, tracing of Clarno Formation debris flow deposits into proximal and vent facies has been done thus far only at Keyes Mountain (Oles and Enlows, 1971). The most widespread and mapped volcaniclastic unit in the Clarno Unit area with potential for volcanic facies analysis is the conglomerate of the "Palisades." This unit is generally coarse-grained throughout the mapped area and contains very coarse-grained channel facies debris flow deposits in the "Palisade" cliffs. The debris flow units are laterally continuous for 5-15 km in the Clarno area and onlap hilly topography to form an upper planar surface. Sets of debris flows with no paleosol interbeds are common in these debris flow packages. These sets of debris flows are separated by weak to moderately developed paleosols whereas the mappable debris flow packages, such as the conglomerate of the "Palisades" and the conglomerate of Hancock Canyon are separated by well-developed paleosols. The debris flow sets are interpreted as the product of syn-eruptive sedimentation from one eruptive episode and the whole mappable debris flow package probably represents the main eruptive period of a medium-sized volcano. Such a large debris flow apron with little proximal-distal clast size change and largely lacking fluvial conglomerates probably represents a large alluvial apron which flanked a large volcano. If this were a braidplain, then fluvial conglomerate beds would be interbedded with debris flows. This interpretation supports the conclusion of White and Robinson (1992) that the Clarno Formation volcaniclastic deposits accumulated in volcanic flank and apron settings, but is an exception to the conclusion of White and Robinson (1992) that the volcanoes responsible for Clarno Formation deposition were small.

Depositional Setting of Fossil Sites in Conglomerate of Hancock Canyon Conglomerates of Hancock Canyon have a mix of debris flow deposits, fluvial conglomerates and tuff beds. Compared to the conglomerate of the "Palisades," the conglomerate of Hancock Canyon, with their abundance of flood surge or hyperconcentrated deposits and fluvial reworked beds, indicate a lower gradient or more distal depositional setting. Additionally, the mixed nature of the deposits with their numerous thin tuff beds indicates a braidplain setting. Lateral variation of this conglomerate unit from a mixed debris flow and fluvial package with tuff beds to a package of coarser-grained debris flows from west to east indicates a braidplain to apron transition in this direction.

Within the Clarno area are numerous fossil plant localities (including several new sites, see Bestland and Retallack, 1994a) that indicate apparently dissimilar climates. The classic "Nut Beds" site yields plant fossils strongly indicative of a tropical to paratropical climate (Manchester, 1981, 1994). In contrast, at the same stratigraphic level and in a similar debris-flow depositional environment, some fossil plants found in Hancock Canyon suggest temperate conditions. It is likely that the "Nut Beds" flora represents a lowland, floodplain rainforest, like the selva of tropical Mexico, whereas the "Hancock Tree" flora represents an early successional forest located on an unstable braidplain. The flora has similarities to higher altitude forest of cooler climatic affinities like the *Liquidambar*-oak forests of Mexico (Gomez-Pompa, 1973).

Paleosols and Overbank Deposits An overbank to piedmont alluvial setting is interpreted for the "Red Hill" claystones based on laterally continuous paleosol horizons present in "Red Hill" and channel conglomerates interbedded with the claystones. A terraced alluvial bottomland was also probably a component of the depositional setting, considering gleyed paleosols (Scat and Sitaxs) at a few levels in "Red Hill." The upper "Red Hill" section contains a thick stack of red Luca paleosols with few gleyed intervals. A large channel-fill conglomerate is interbedded with the claystones of "Red Hill" at the Gable (Bestland and Retallack, 1994a) indicating that large channels did exist on the alluvial plain.

Thick accumulations of alluvial paleosols occur in scattered pockets elsewhere in the Clarno Formation. Their distribution is not widespread probably due to rapid aggradation of coarse-grained units which was followed by incision during volcanic quiescence. Only occasionally did alluvial plains exist for any length of time during which finer-grained alluvium accumulated. "Red Hill" sits stratigraphically near the top of the Clarno Formation and probably marks the end of explosive andesitic volcanism in this part of the Clarno arc.

John Day Formation Depositional Setting

The John Day Formation represents a non-marine backarc basin that received mostly pyroclastic detritus form Cascade sources to the west. The formation becomes finer-grained from west to east following the dispersal pattern of pyroclastic material (Fisher, 1966a; Robinson and others, 1984). Previous workers (Robinson and others, 1984; Robinson and others, 1990) have inferred an andesitic composition for the alluvial deposits of the John Day Formation based on the abundance of sanidine, scarcity of biotite and quartz, and the interpretation that the Western Cascade andesite stratovolcanoes were its source. However, the ash flow tuffs of the John Day Formation contain sanidine and quartz and are rhyolitic (Robinson and others, 1990). Additionally, geochemical analysis of tuff beds (Hay, 1962, 1963; Fisher, 1966a) and C horizons of paleosols (Fisher, 1966a; Getahun and Retallack, 1991; Bestland and Retallack, 1994a,b) indicate a rhyolitic to rhyodacitic composition for the tuffs and tuffaceous alluvial deposits. The John Day ash-flow tuffs of the western facies are relatively homogenous in composition and differ from the biotite and quartz-rich rhyolitic tuffs of the Western Cascades, such as the 35 Ma Bond Creek Tuff (Smith and others, 1980). The western facies ash flow tuff sheets thicken toward the Warm Springs and Mutton Mountain areas. Taken together, these facts support an interpretation of a rhyolitic source for the John Day Formation that was separate from the Western Cascades.

Alluvial Paleosols The thick, colorful claystone and tuff sequences so well known from the John Day and Clarno formations have been historically problematic in terms of interpretations of depositional environment. Hay, (1962 and 1963), interpreted the John Day tuffaceous claystones as massive airfall tuffs variously affected by pre-burial weathering. Other interpretations of the fine-grained sequences include lacustrine silts and claystones (Oles and Enlows, 1971), and loess (Fisher, 1966b). In this paper, and previously (Retallack, 1981, 1991a, b; Bestland and others, 1996, 1997; Bestland, 1997), we interpret most of the claystones and tuffaceous claystone beds of the John Day and Clarno formations as paleosol horizons. Furthermore, most of the paleosols and their associated, although pedogenically modified, substrate, are interpreted as alluvial, and in a few cases colluvial, deposits. Many different paleosol horizons have been identified and interpreted (Bestland and Retallack, 1994a, b), and these paleosols can be broadly grouped into floodplain setting (alluvial) and hillslope setting (colluvial) soil forming environments. Landscape aggradation in the form of floods, pyroclastic airfall, wind blown dust and ash, and colluvial movement from up-slope locations caused vertical accretion of soil horizons. Larger-scale additions of alluvium and colluvium periodically buried the landscape and caused new soils to form on these deposits. Aggradational periods were interspersed with episodes of downcutting during which the alluvial and colluvial basin fill would be partially removed (Bestland and others, 1997). Most of the paleosols in the John Day and Clarno formations are interpreted as floodplain paleosols based on the following general considerations. They are relatively laterally continuous and show evidence of both well and poorly drained conditions. They lack coarse-grained channel bodies, thus indicating the predominance of vertical floodplain accretion.

Eocene-Oligocene Transition

The long stratigraphic sequence of paleosols in the upper Clarno and lower John Day Formations record a dramatic paleoclimatic change. This is the transition from the Eocene to the Oligocene when the Earth's climate and biota changed from the warm, mostly subtropical world of the Mesozoic and early Cenozoic, to the glaciated world of today, or from the "hot house" to the "cold house" (Prothero, 1994). These climatic and biotic changes are centered around the Eocene-Oligocene boundary with the changes appearing to be stepwise over several million years on either side of this boundary (Wolfe, 1978; Miller and others, 1987, 1991; Bestland and others, 1997).

Recent work on the timing and global correlation of the Eocene-Oligocene boundary (Swisher and Prothero, 1990; Prothero and Swisher, 1992; Cande and Kent, 1992) allows for a comparison of the stratigraphy and age determinations from the central Oregon stratigraphy with the global data base of climate change (Bestland and Retallack, 1994c). Much of the existing global climate change data come from deep sea sediments and their oxygen and carbon isotopic record (Fig. 13). Paleosols have also been used as evidence of global climate change over this age span (Retallack, 1983; 1992). In the John Day Formation climatic steps centered around the Eocene-Oligocene boundary correspond with member boundaries (Bestland and others, 1994, 1997). Most notable from this stratigraphic study of paleosols is the abruptness of the Eocene-Oligocene climatic transition. The short time span of this change is not apparent from paleontological evidence of vertebrates and plant fossils in the Pacific Northwest because of the incompleteness of the fossil record. The paleoclimatic record from paleosols in the Clarno and John Day formations, in contrast, is much more complete.

Paleoclimate and Tectonic Summary

In the Clarno area, these paleoclimatic changes are evident in the five different paleosol facies that are contained in the upper Clarno and lower John Day Formation. Paleosol types (pedotypes in the sense of Retallack, 1994) make up these paleosol facies (Table 1). In each paleosol facies, one pedotype is representative of the optimum degree of weathering that occurred under a particular depositional setting and paleoclimate. These paleosol types are the most developed paleosols in the section, but are not residual paleosols (as is the Pswa pedotype). They are also from well-drained soil forming environments. In stratigraphic order the pedofacies are: 1) conglomeratic debris flow dominated deposits contain Patat pedofacies, 2) lower "Red Hill" claystones contain Lakayx pedofacies, 3) upper "Red Hill" claystones and lower Big Basin member contain Luca pedofacies, 4) siltstones of the "Hancock Quarry" contain Micay pedofacies, 5) middle Big Basin Member contains Ticam pedofacies (Bestland and Retallack, 1994b).

In the conglomeratic deposits (conglomerates of the Palisades and conglomerates of Hancock Canyon), only weakly developed paleosols are present between some debris flow deposits. Sedimentation rates were high and time intervals between episodes of eruption and sedimentation where short, consequently, the paleosols are Entisol and Inceptisol-like paleosols. The Inceptisols-like paleosols, referred to as Patat and Sayayk pedotypes, represent 10's to 100 yrs of soil formation and their geochemical compositions are not much different from the andesitic to dacitic parent alluvium.

In the lower part of "Red Hill," strongly developed, Ultisol-like paleosols of the Lakayx pedotype are present and represent a dramatic change in depositional setting from an active volcaniclastic apron of the conglomerates of Hancock Canyon to a quiet floodplain. This change represents the cessation for a long period of time of proximal volcanic activity in at least this part of the Clarno Formation. Each Lakayx type paleosol represent approximately 50,000 years of soil formation in a humid subtropical climate (Bestland and Retallack, 1994a). These paleosols and their associated poorly drained Scat pedotypes are the most weathered paleosols in the upper Clarno and lower John Day formations in the Clarno Unit area.

In the upper part of "Red Hill," strongly developed Alfisol-like paleosols of the Luca pedotype dominate the section. Each Luca paleosol represents 20,000-50,000 years of soil formation in a humid subtropical climate (Bestland and Retallack, 1994a). The change from Ultisol-like Lakayx to Alfisol-like Luca paleosols is interpreted to be the result of climatic cooling and drying during the late Eocene. This break between the lower and upper "Red Hill" claystones may correlate to a period of oceanic cooling centered around paleomagnetic time interval chron R19 (reversed) which is thought to be caused by a major plate tectonic reorganization, best expressed by the bend in the Hawaiian-Emperor seamount chain but also recorded in new spreading in the Indian Ocean (Williams, 1986). The age of chron R19 has recently been adjusted to approximately 42 Ma by Cande and Kent (1992) which fits well with our 42.5 Ma estimated age of the boundary between the lower and upper "Red Hill" claystones (Fig. 13). Changing patterns of oceanic circulation and volcanism are the hypothesized causes for this climatic change (McGowan, 1989). The R19 plate tectonic reorganization may have caused the change from Clarno arc subduction to Cascade arc subduction. By this reasoning, "Red Hill" marks the end of voluminous Clarno volcanism. The change in paleosol type from lower to upper "Red Hill" marks the climatic change set in motion by the plate tectonic reorganization. The hiatus in volcanism recorded in the "Red Hill" section from 44 Ma to about 40 Ma, when John Day or Cascade volcanism began, is correlated to Gresens (1981) Telluride erosion surface and in central Oregon was a period of sporadic volcanism transitional from the Clarno to the Cascade arc.

Following this volcanic hiatus of approximately 2-4 million years, renewed volcanism, represented by the andesite of Horse Mountain, rejuvenated the alluvial system with fresh andesitic material and caused the deposition of the "Hancock Quarry" beds. More rapid alluvial aggradation and fresh andesitic material changed the soil type from red and clayey "Red Hill" type paleosols to the brown Inceptisol-like paleosols in the "Mammal Quarry" siltstones. These paleosols are too weakly developed to interpret much in the way of paleoclimate, except that it was humid and relatively warm.

With the onset of John Day volcanism, the dominant alluvial material changed from andesitic detritus to fine-grained rhyodacitic ash. In the late Eocene, lower Big Basin Member strata in the Clarno Unit area contain strongly developed Alfisol-like paleosols of the Luca pedotype. These are the most weathered of the paleosols in this thick and varied section. The geochemical composition of these John Day Luca paleosols are much the same as Clarno Luca paleosols and indicate little if any climatic change from late Clarno time to early John Day time. Not until approximately 34 Ma at the Eocene-Oligocene boundary did the climate change dramatically. Paleosols formed after this transition are higher in bases and lower in Fe and Ti than similar Eocene paleosols. In the Clarno area this boundary is marked by the change from the lower Big Basin Member to the middle Big Basin Member, or from Luca pedofacies to Ticam pedofacies. The change from subtropical to temperate conditions across this boundary is contrasted dramatically by comparing the Eocene “Nut Beds” flora and “Red Hill” Lakayx paleosols with the Oligocene Bridge Creek flora (“Slanting Leaf Beds”) and middle Big Basin Member Ticam paleosols.

Acknowledgments

This report represents the combined efforts of E.A. Bestland and G.J. Retallack under contract with the National Park Service (Bestland and Retallack, 1994a, b), the University of Oregon Geology Field Camp and its director, M.Allan Kays, and Portland State University Geologic Field Methods directed by P.E. Hammond. Discussion with T. Fremd, J. Jones, E. Taylor, R. Goodfellow and A. Mindzenty have added to our understanding of the geology and paleontology of this area.

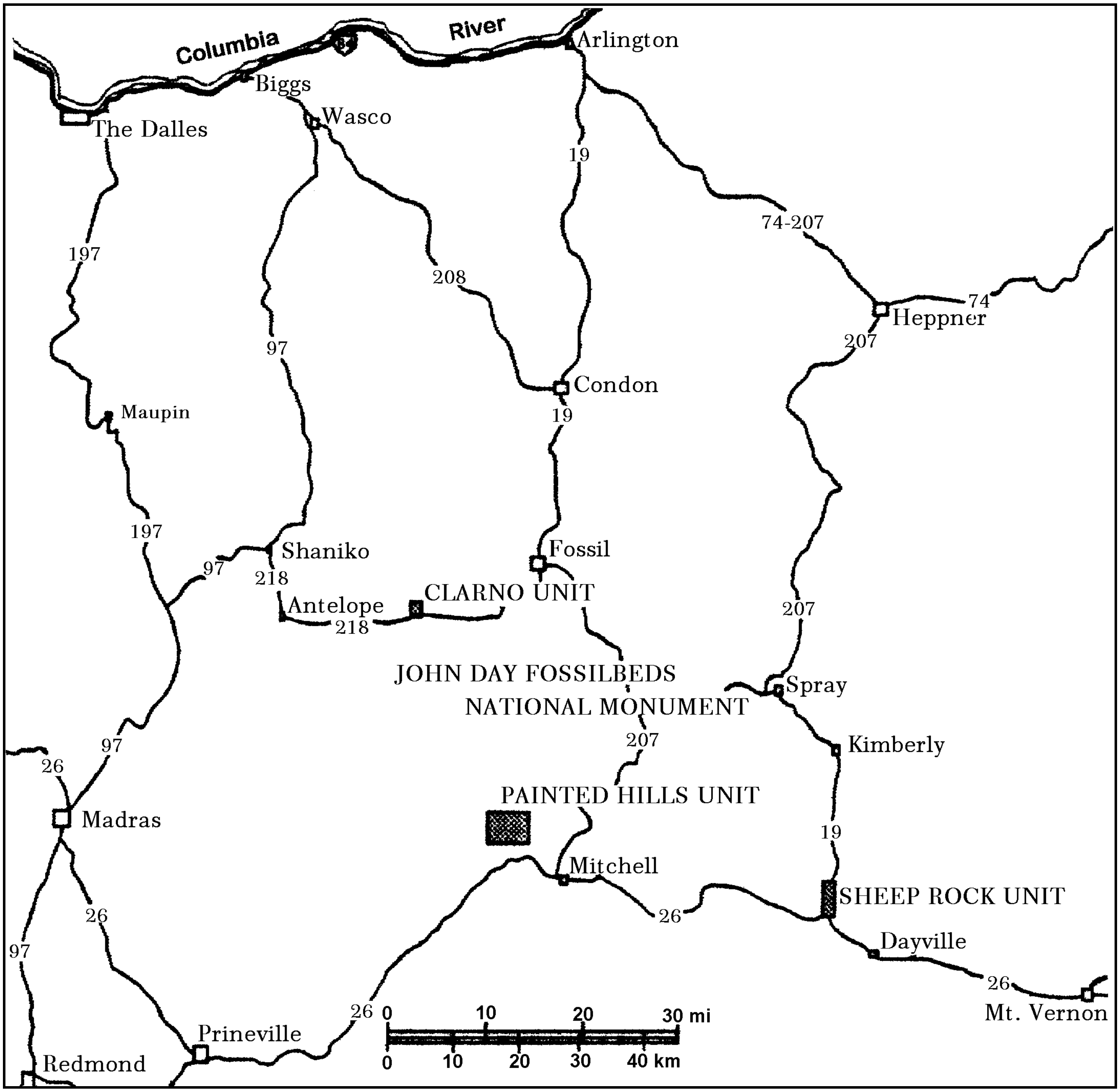


Figure 1. Location map of north-central Oregon showing units of the John Day Fossil Beds National Monument and major access roads.

Figure 2. Composite stratigraphic section of the upper Clarno and lower John Day Formations in the Clarno Unit of the John Day Fossil Beds National Monument. Diagram shows informally recognized stratigraphic units and corresponding age determinations. For explanation of symbols to units, see geologic map of Figure 3. Additional symbols are: brn (brown); cgl (conglomerate); clst (claystone); ss (sandstone); st (siltstone); wh (white).

EXPLANATION

Rock units are symbolized here the map without the usual peri designation: in this case, "Q" fo Quaternary surficial units and "T" fo all other, Tertiary, units.

Surficial deposits

a	Alluvium
ls	Landslide
ta	Talus
p	Pediment

Bedrock units

crb	Columbia River Basalt Group

John Day Formation

jmb	Middle and upper Big Basin mem
jfb	Member F basalts
jlb	Lower Big Basin Member clayst
jft	White tuff of member F
jba	Member B basaltic andesite
jat	Welded tuff of member A

Clarno Formation

cmq	Siltstone of Hancock Mammal Qu
cah	Andesite of Horse Mountain
cau	Upper andesite of Horse Mounta
crh	Claystone of Red Hill
cha	Andesite of Hancock Canyon
crg	Conglomerate
cct	Tuff of Currant Creek
chb	Basalt of Hancock Canyon
cch	Conglomerate of Hancock Cany
cawf	Andesite of West Face Cliffs
ccp	Conglomerate of The Palisades
cap	Andesite of Pine Creek
cl	Lower Clarno Formation
cd	Hancock dacite dome

Contact

Indefinite contact

45 Strike and dip of bedding

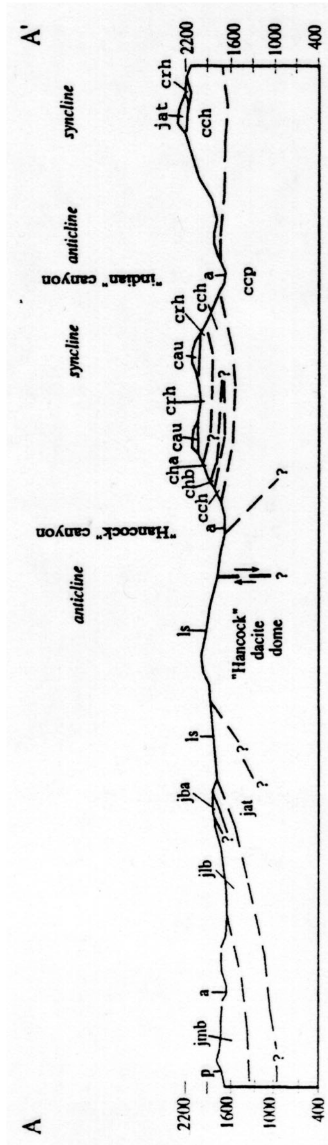
U D Fault, showing displaceme U=upthrown side, D=downthrown side

Indefinite fault

Fold axis, showing plunge

Anticline

Syncline



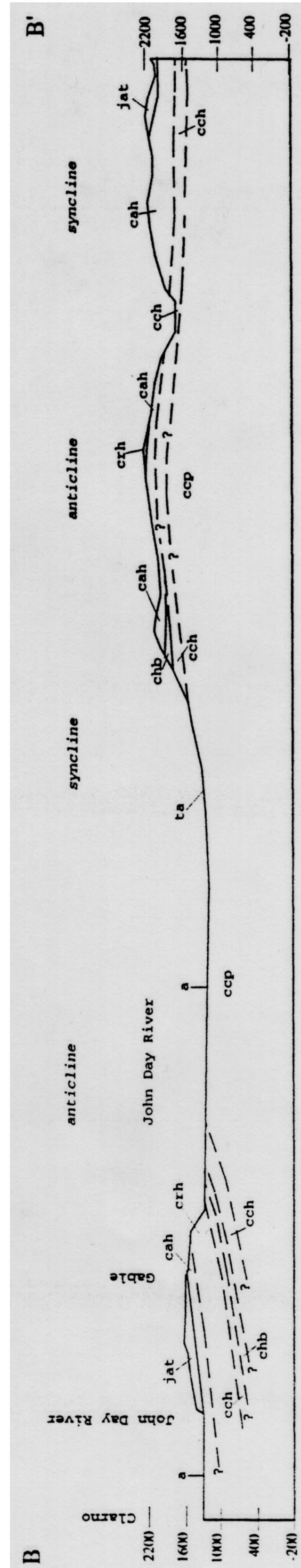


Figure 3. Geologic map of the Clarno Unit of the John Day Fossil Beds National Monument and vicinity (modified from Bestland and Retallack, 1994a; unpublished mapping by P.E. Hammond and Portland State University students; and unpublished mapping by M.A. Kays, D.L.S. Blackwell, J. Stimac, E.A. Bestland and others).

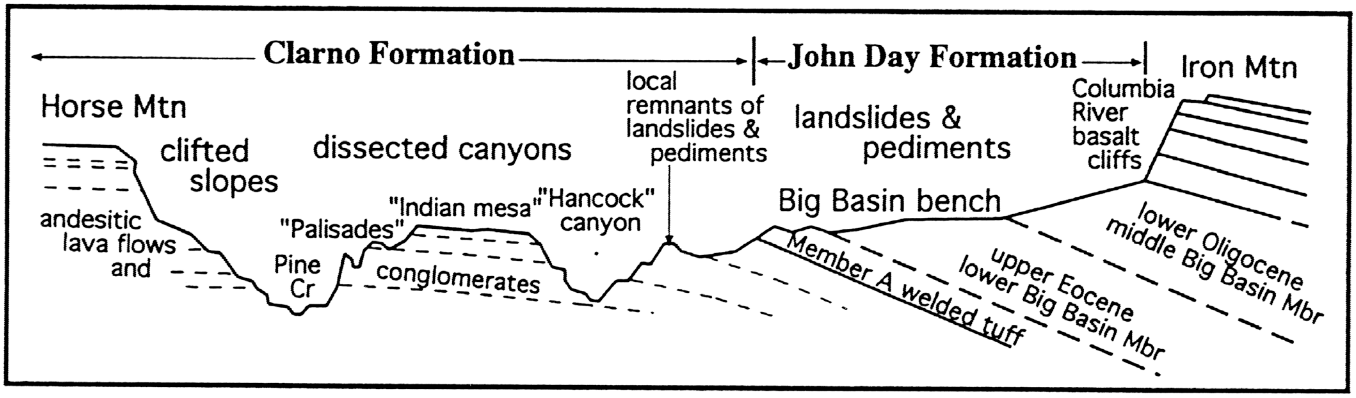


Figure 4. Sketch cross-section of the Clarno area illustrating the physiographic differences between the dissected canyons of the Clarno Formation, the broad gently sloping benches of the lower John Day Formation and the prominent cliffs of the Columbia River Basalt Group.

Figure 5. View looking east of the margin of the dacite dome and onlapping strata. A series of trenches were dug down to bedrock at this location and which documented the onlapping nature of a series of colluvial paleosols on to the dacite igneous body (Bestland and Retallack, 1994a).

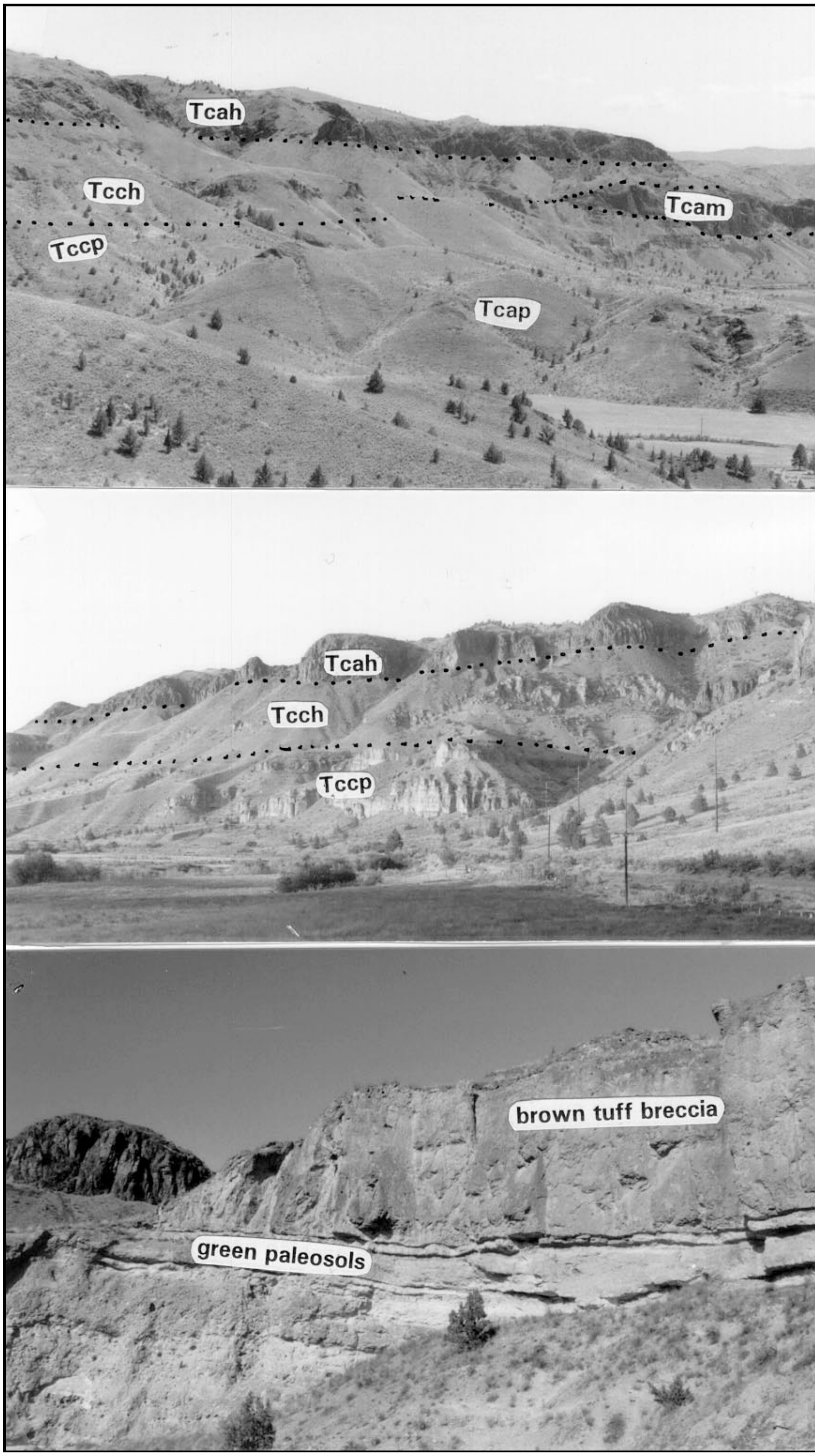


Figure 6. Photographs of “West Face Cliffs.” A) View looking south toward Horse Mountain showing the following lithostratigraphic units in the Clarno Formation (Tcap-andesite of Pine Creek, Tccp-conglomerate of the “Palisades,” Tcam-andesite of “West Face Cliffs,” Tcch-conglomerate of Hancock Canyon, Tcah-andesite of Horse Mountain). B) View looking north at the “West Face Cliffs.” C) Debris flow deposits and paleosols in conglomerate of the “Palisades” in the “West Face Cliffs.”

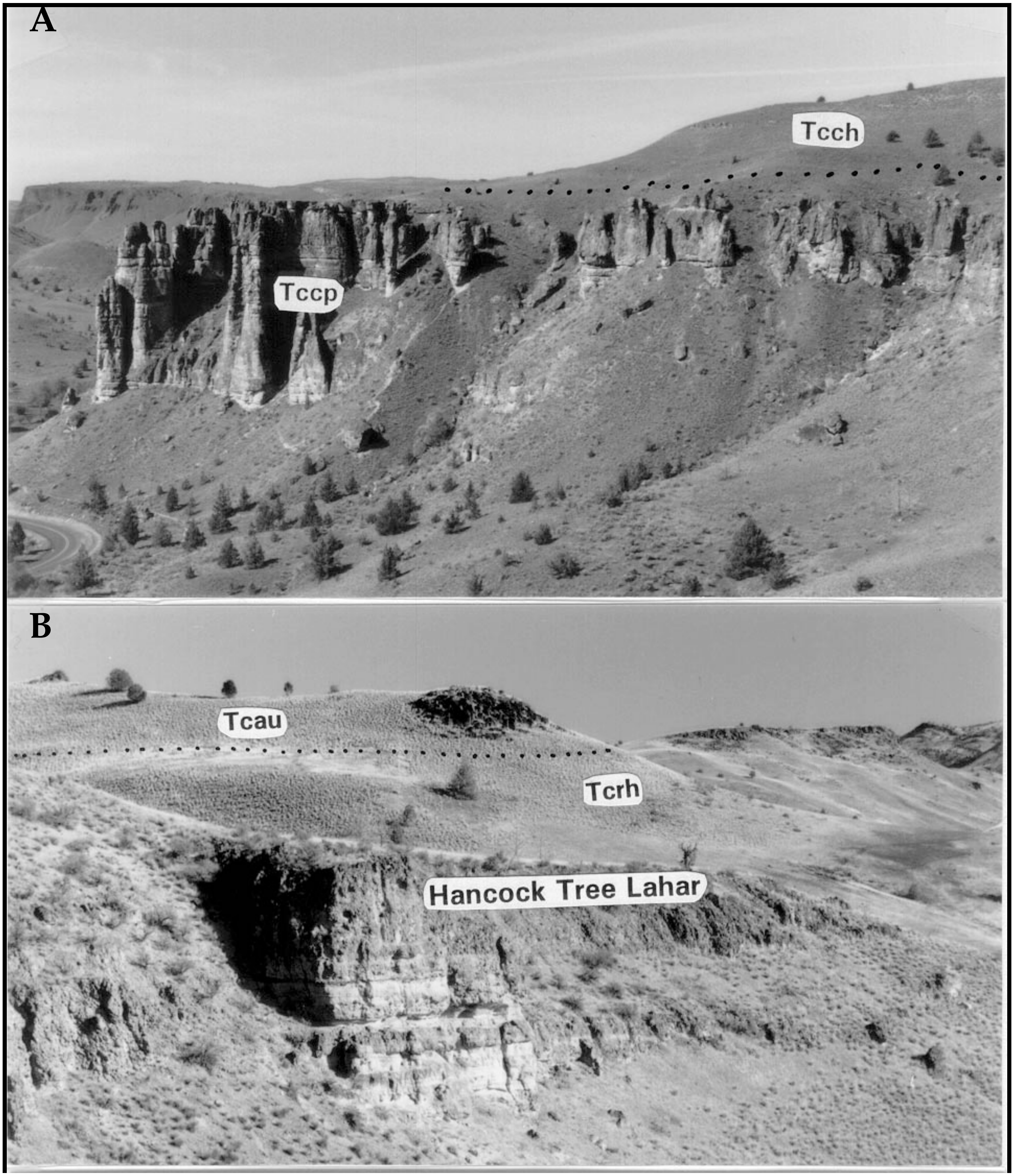


Figure 7. Photographs of the “Palisades” and Hancock Canyon. A) View looking west of the conglomerates of the “Palisades” overlain by bench-forming claystone unit which in turn is overlain by conglomerates of Hancock Canyon. B) View looking east of the conglomerate of Hancock Canyon overlain by claystone of “Red Hill” and the upper andesite unit.

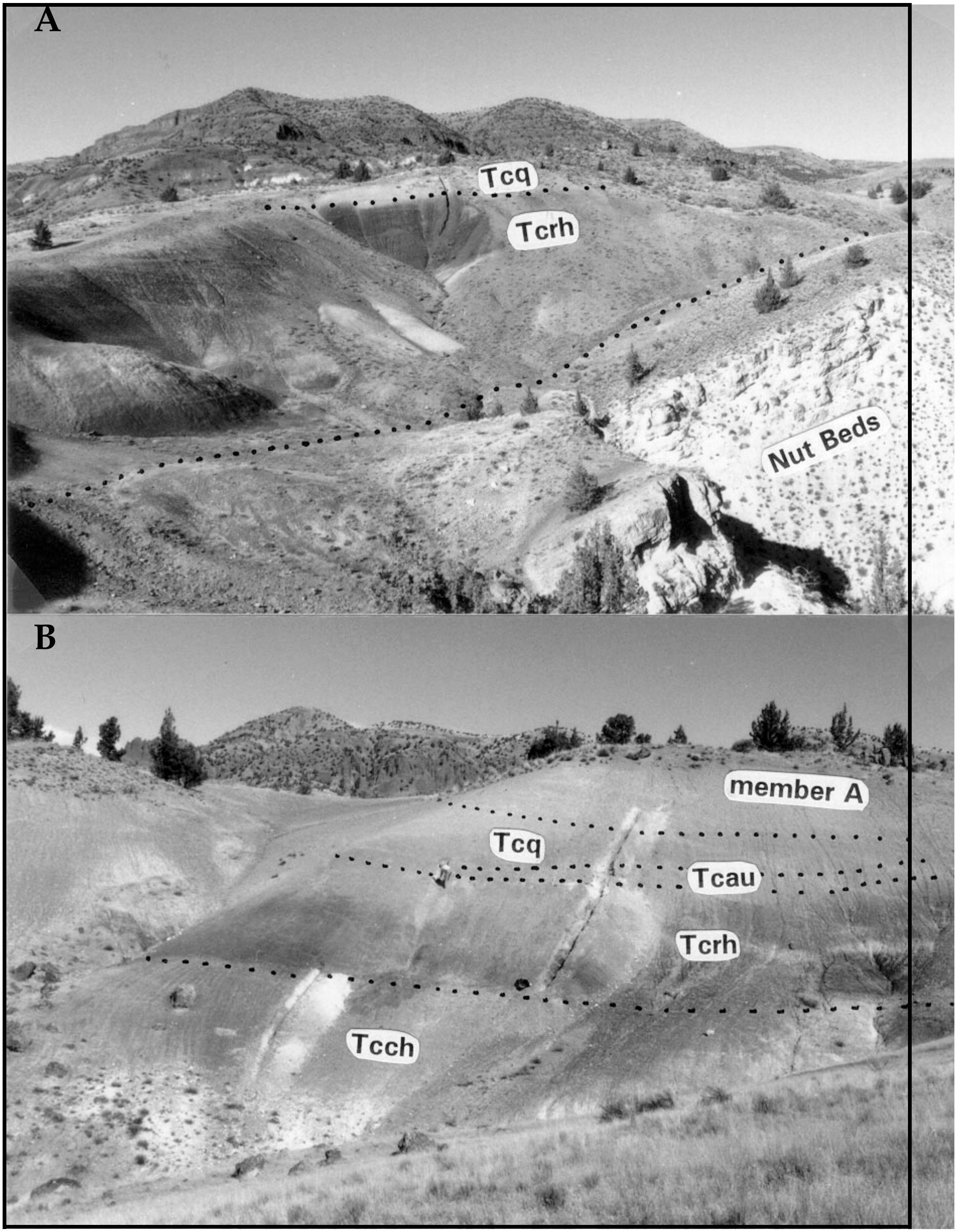


Figure 8. Photographs of upper Clarno Formation units. A) View looking north of “Red Hill” and lithostratigraphic units in upper Clarno Formation (“Nutbeds” is in the upper part of Tcch-conglomerate of Hancock Canyon, Tcrh-claystone of “Red Hill,” Tcq-mammal quarry beds). B) View looking north of “Red Hill East” and lithostratigraphic units exposed in the badlands.

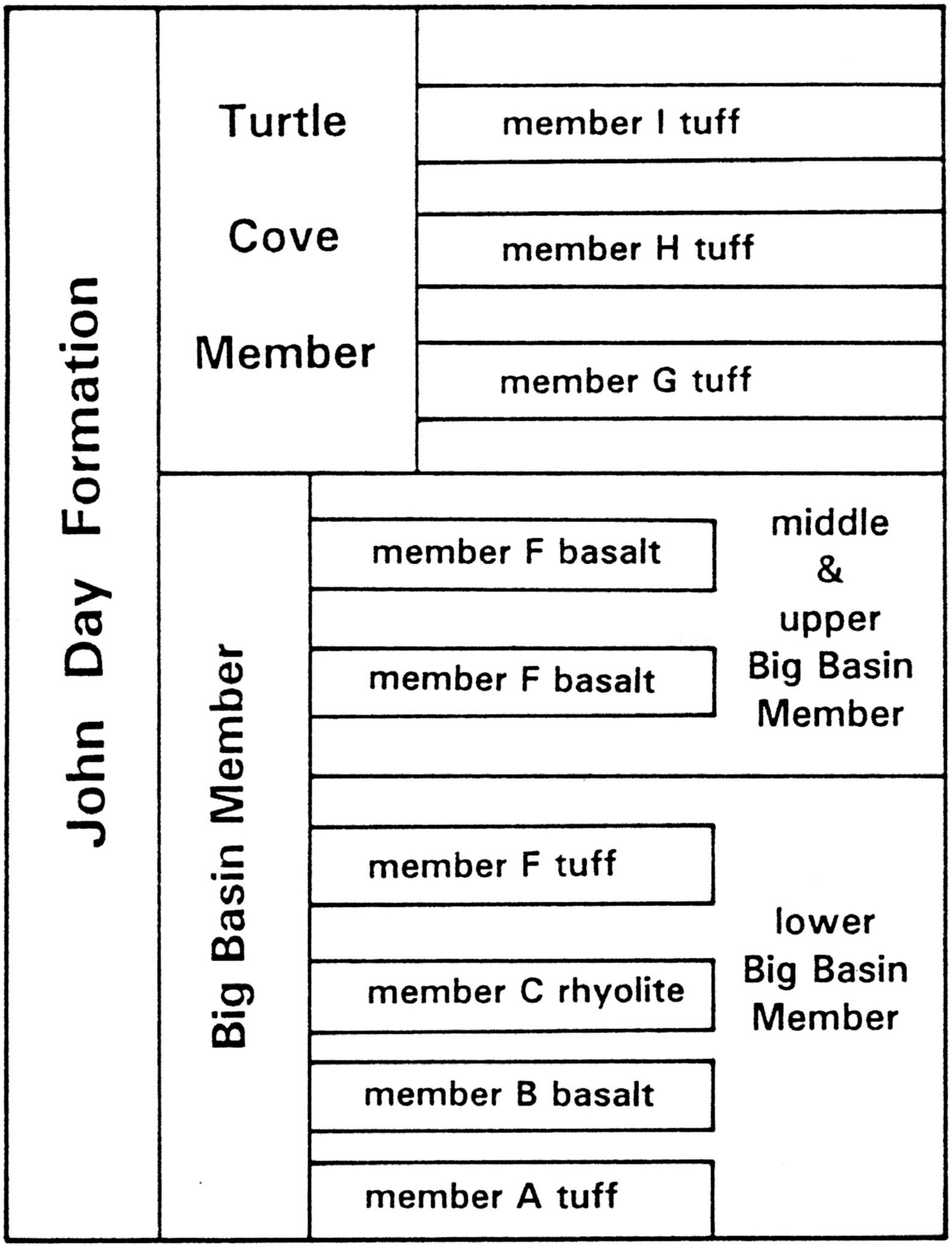


Figure 9. Stratigraphy of the John Day Formation in the Clarno area. Stratigraphic units combine informal divisions of the western facies of the John Day Formation (after Peck, 1964, Robinson, 1975, and Robinson and others, 1984) with eastern facies formal divisions of Fisher and Rensberger (1972) as modified by Bestland and others (1997).

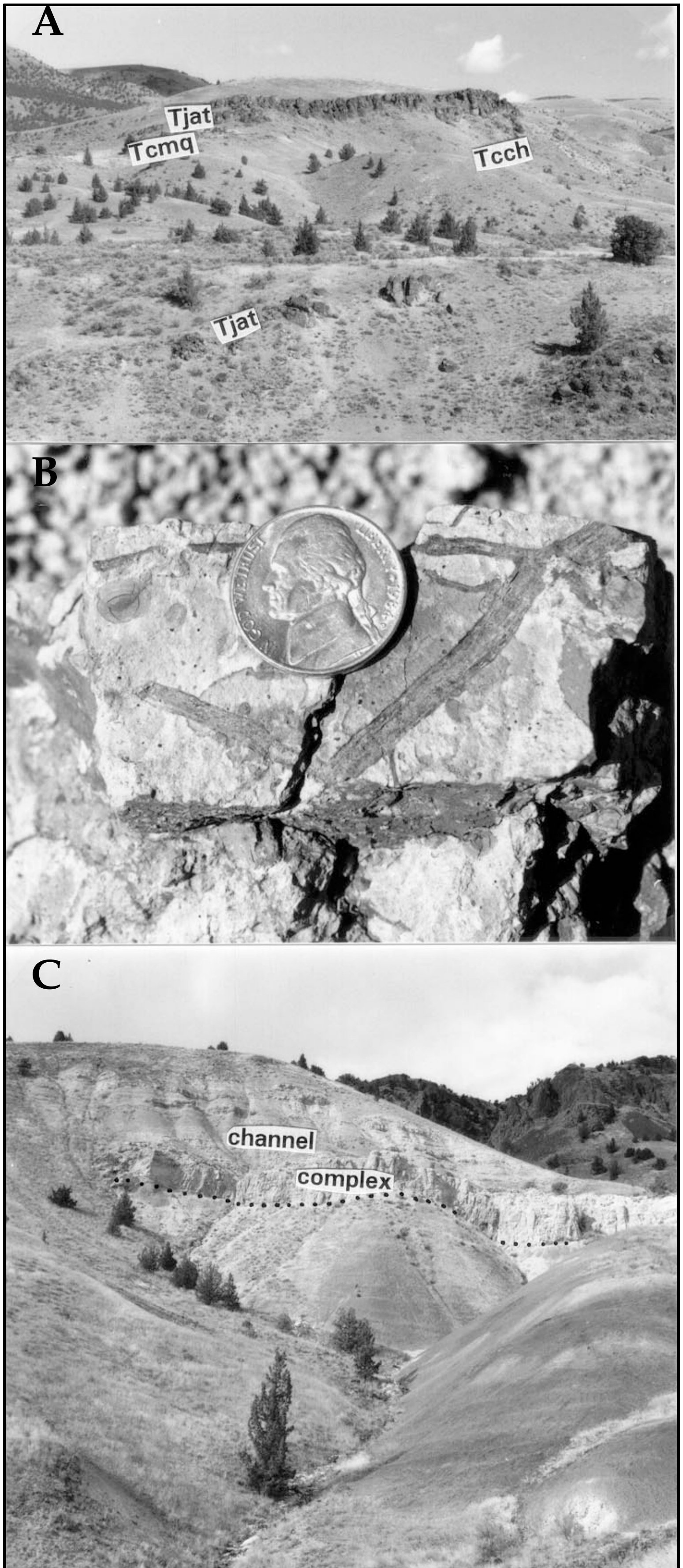
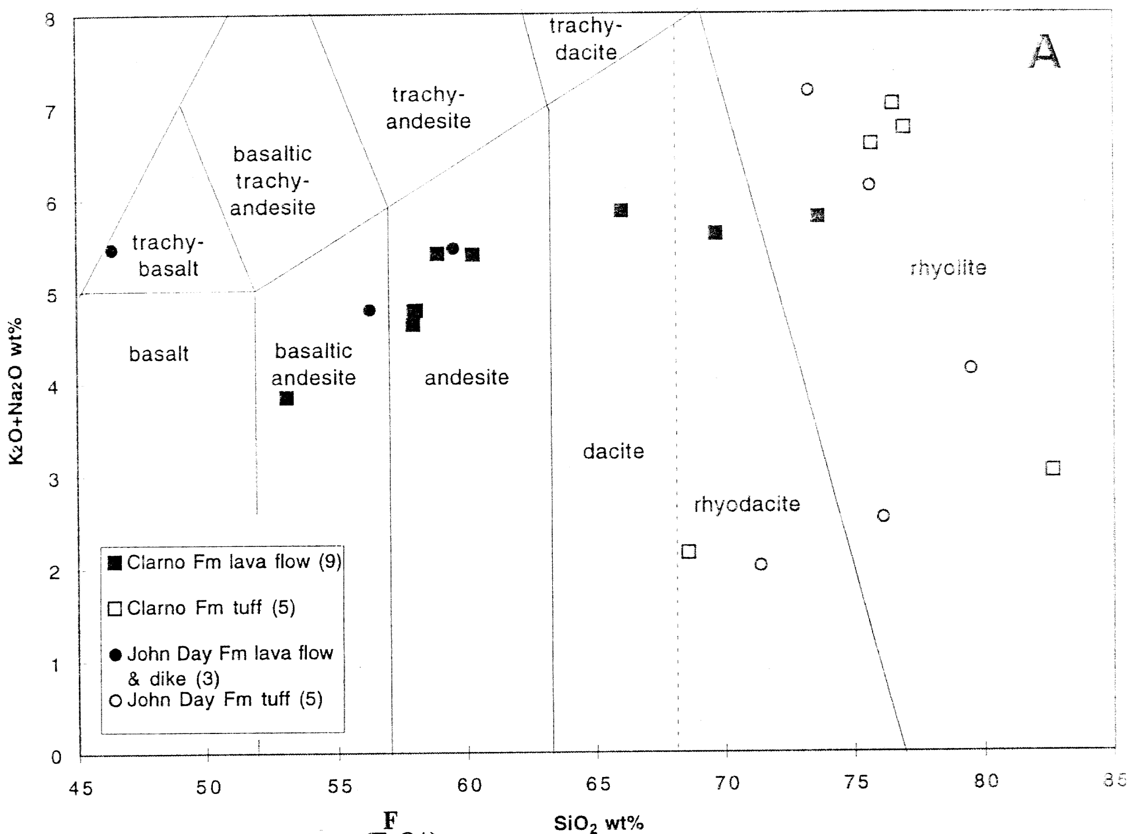


Figure 10. Photographs of lower John Day Formation. A) View looking east of mammal quarry area and the welded tuff of Member A of the basal John Day Formation (unit Tjat) which overly the "mammal quarry beds" (unit Tcmq), and the conglomerate of "Hancock Canyon" (unit Tcch). B) Carbonized plant debris and accretionary lapilli from the unwelded base of the member A tuff. C) Tuffaceous claystone of the lower Big Basin member overlain by siltstone channel deposits.



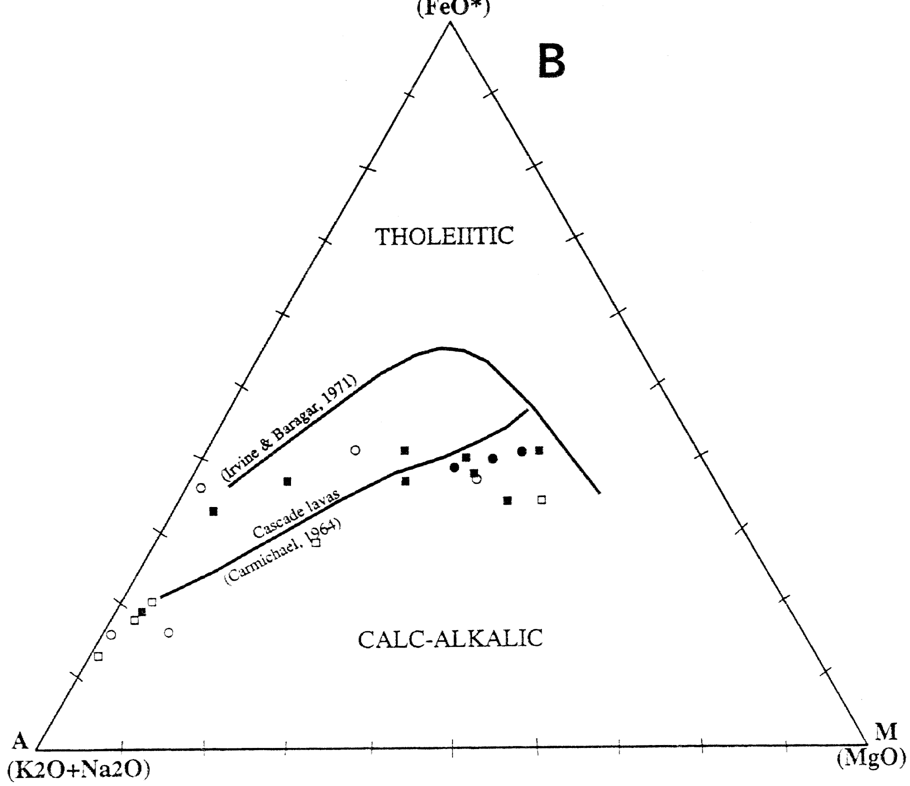


Figure 11. A) Total alkali-silica diagram of Clarno and John Day formation lavas and tuffs (after Le Maitre and others, 1989). Samples plotted are listed in Table 2 and described in Table 3. Number of data points is shown after each rock type. Division between dacite and rhyodacite is from Swanson (1991). B) AFM diagram after Irvine and Baragar (1971) of compositional trends of rocks from the Clarno area and boundary between calc-alkaline and tholeiitic fields.

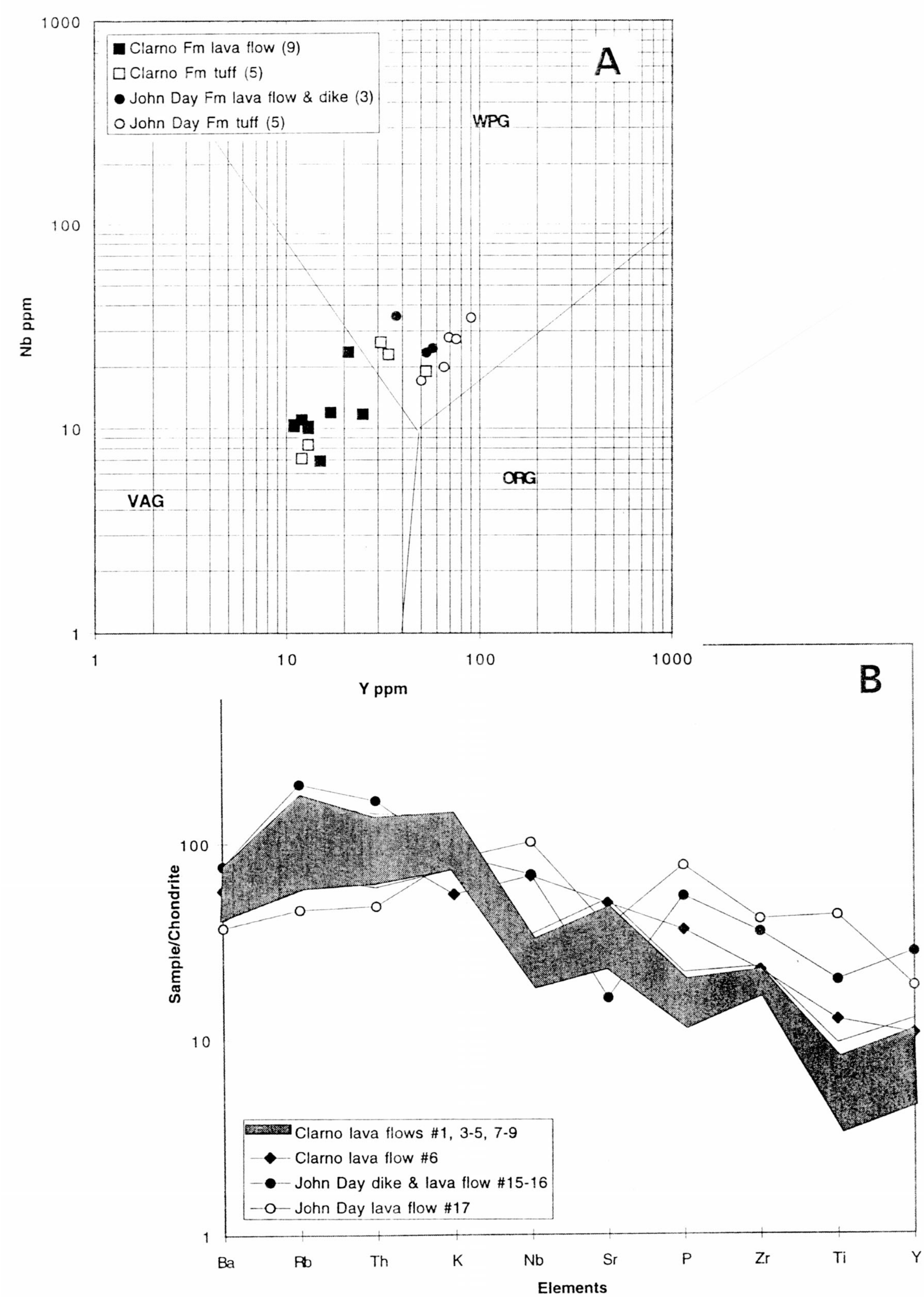


Figure 12. A) Nb-Y discrimination diagram for rocks of granitic composition (after Pearce and others, 1984) showing tectonic setting for rock units of the Clarno area. VAG (volcanic arc granitic rocks; ORG (ocean ridge granitic rocks); and WPG (within plate granitic rocks). B) Spidergram (after Thompson, 1982) showing compositional variation in rocks from the Clarno.

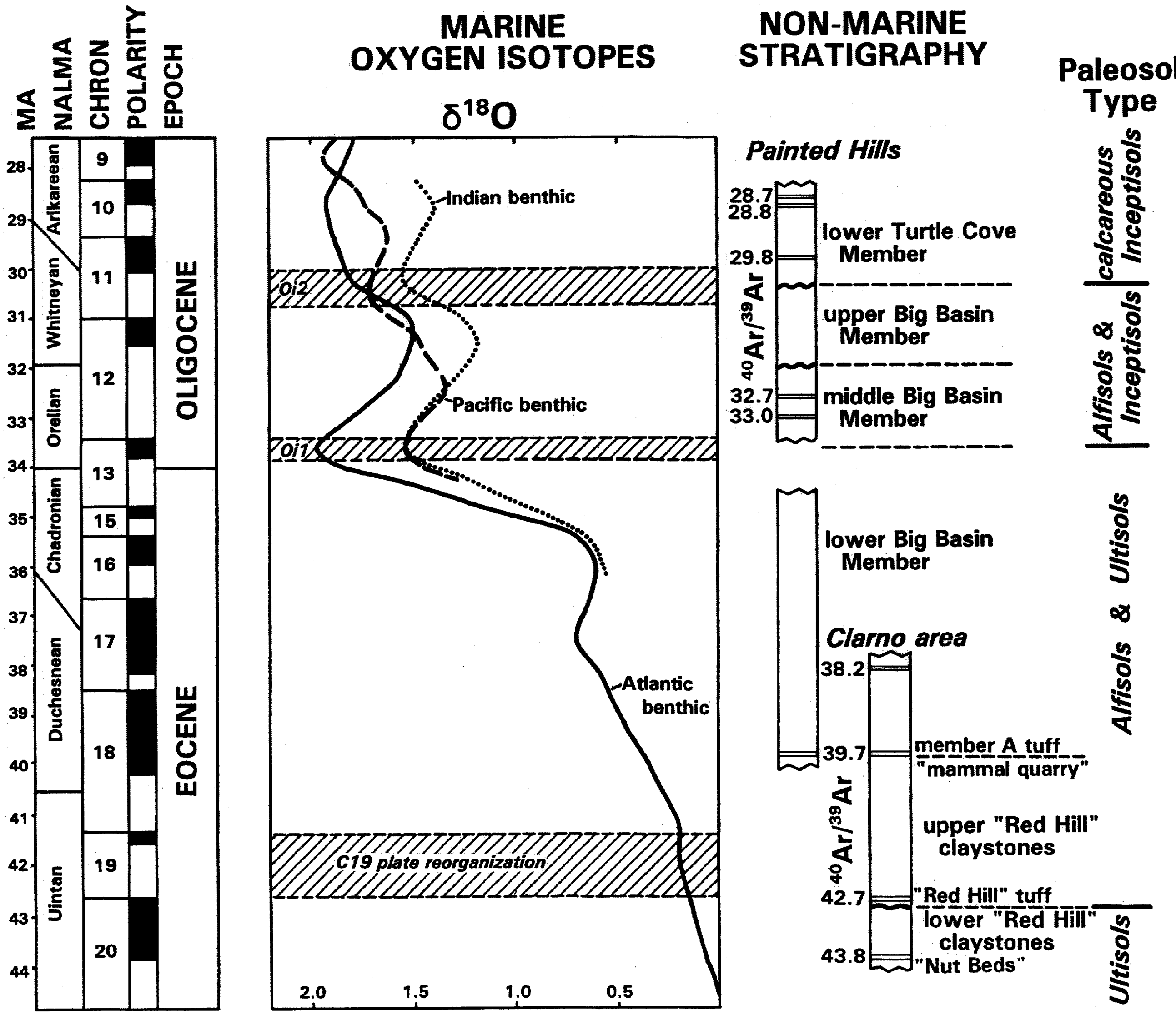


Figure 13. Correlation of non-marine stratigraphy from central Oregon with marine oxygen isotopic record using the geomagnetic time scale of Cande and Kent (1992, 1995), as modified by Berggren et al. (1992, 1995), and $^{40}Ar/^{39}Ar$ radioisotopic age determinations from tuffs interbedded with paleosols. The Eocene-Oligocene boundary is placed at 34 Ma (Swisher and Prothero 1990; Berggren et al. 1995). Marine isotopic data is from benthic foraminifera and smoothed by linear interpolation (Miller et al. 1987). Oi1 and Oi2 are oceanic oxygen isotope cooling events (Miller et al. 1991). The first major change in paleosol type occurs between the lower and upper red claystones of the Clarno Formation and corresponds with the chron 19 plate tectonic reorganization (McGowran 1989). The dramatic change in paleosol type and the large truncation surface between the lower and middle Big Basin Members supports the placement of the Eocene-Oligocene boundary at approximately 34 my Ma based on $^{40}Ar/^{39}Ar$ age determinations from the central Oregon section. An early Oligocene climatic recovery is indicated by the presence of well developed, clayey paleosols at the top of the middle Big Basin Member approximately dated at 32.0 to 32.7 Ma. A third major change in paleosol type between the upper Big Basin Member and lower Turtle Cove Member, at approximately 30 Ma, is synchronous with the Oi2 oceanic oxygen isotope cooling event.

ons of soil analogues from the
American language (Delancey

	Soil Development	Soil Identification
'3	strong to very strong	Ultisols-Haplo-humult
	moderate	Eutric Histosol
;9	strong to very strong	Ultisols-Hapludult
;7	moderate to strong	Alfisols-Hapludalf
;6	moderate to weak	Inceptisols-Eutrochrept
'3	weak to moderate	Inceptisols-Eutrochrept
.8	moderate	Alfisols-Lithic Hapludalf
ł3	moderate	Inceptisols-Hapl-umbrept
!1	weak to moderate	Inceptisols-Placaquept
)9	moderate	Inceptisols-Andic Eutro chrept

earth with impersistent clayskins. 10.97
(middle and upper Big Basin Member sequences)

Table 2. Chemistry and mode of selected units in Clarno and John Day Formations in Clarno Unit and vicinity

Formation	Clarno Formation-lava flows									Clarno Formation-tuffs					John Day Formation-lava flows			John Day Formation-tuffs					Formation
Number (on map)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Number (on map)
Lab number	PHA93602	PHA93611	PHA93603	PHA91618	PHA93631	PHA91613	PHA91602	PHA93634	PHA91609	PHA93612	PHA93644	PHA94603	PHA93609	PHA93653	PHA91607	PHA93614	PHA93651	PHA94055	PHA94057	PHA93615	PHA95610	PHA95605	Lab number
Unit	Hancock dacite dome	clast of rhyodacite	andesite of Pine Creek-west lobe	andesite of Pine Creek-east lobe	middle andesite West Face Cliffs	amygdaloidal mafic andesite	andesite of Han- cock Canyon	andesite of Horse Mtn.	upper andesite of Horse Mtn.	white fern-leaf tuff	tuff of Currant Creek at Gable	tuff of Currant Cr. at type area	white tuff below "Nut Beds"	tuff in claystone of "Red Hill"	andesite of Member B	dike to andesite of Member B	basalt of Member F	white tuff at base of Member A	base of welded tuff of Member A	white tuff in up- per Member A	white tuff of Member F	white tuff of "Italian Hill"	Unit
Map symbol	cd	cch	cap	cap	cawf	chb	cha	cah	cau	cch	cct	cct	cch	crh	jba	jia	jfb	jat	jat	jat	jft	jmb	Map symbol
Latitude N	44°55'28"	44°55'20"	44°54'40"	44°54'40"	44°53'17"	44°55'30"	44°55'23"	44°53'27"	44°55'49"	44°55'27"	44°54'26"	44°49'24"	44°55'20"	44°55'23"	44°56'17"	44°55'52"	44°56'14"	44°55'14"	44°55'14"	44°56'09"	46°56'15"	44°56'57"	Latitude N
Longitude W	120°25'35"	120°25'44"	120°26'09"	120°25'12"	120°25'57"	120°25'32"	120°24'58"	120°25'39"	120°24'47"	120°25'03"	120°27'40"	120°33'21"	120°25'49"	120°25'51"	120°24'17"	120°24'35"	120°25'41"	120°27'10"	120°27'10"	120°24'13"	120°24'59"	120°23'40"	Longitude W
UTM N	49977340	4977340	4976098	4976115	4973500	4977635	4977465	4973805	4977530	4977528	4975543	4966015	4977320	4977052	4979140	4978364	4978985	4976380	4976380	4978910	4979062	4980395	UTM N
UTM E	703095	702910	702420	703545	702765	703190	704015	703155	704045	703705	700435	693225	702805	702763	704780	704536	702940	701070	701070	704865	703803	705570	UTM E
major elements																							**major elements**
SiO_2 wt%[1]	67.01	71.92	57.60	57.46	60.35	52.32	65.37	57.85	58.62	75.43	72.75	71.81	79.47	63.28	58.17	55.01	45.96	66.57	71.16	69.33	71.43	6.71	SiO_2 wt%[1]
Al_2O_3	16.36	16.18	5.93	16.47	17.61	15.42	16.83	15.95	17.02	13.04	12.78	11.94	10.01	16.25	13.93	14.17	14.74	16.11	12.24	12.52	11.34	11.53	Al_2O_3
TiO_2	0.372	0.364	0.747	0.774	0.928	1.259	0.617	0.886	0.964	0.337	0.215	0.153	0.042	1.110	1.624	2.369	4.329	0.20	0.649	0.167	.14	0.315	TiO_2
FeO*	2.86	1.40	6.12	6.36	6.29	8.06	4.24	6.82	6.43	1.06	1.69	1.47	1.59	5.80	10.74	11.38	15.07	2.47	4.12	1.18	0.70	2.26	FeO*
MnO	0.052	0.04	0.117	0.125	0.16	0.175	0.291	0.129	0.118	0.016	0.023	0.02	0.012	0.034	0.179	.186	0.212	.09	0.176	0.023	0.024	0.046	MnO
CaO	3.56	1.79	6.87	7.06	6.21	9.51	4.45	7.62	7.00	1.57	1.92	1.40	0.92	2.47	5.56	6.65	7.48	3.63	1.43	2.18	2.43	3.37	CaO
MgO	0.39	0.21	7.19	5.85	2.94	7.69	1.27	5.42	3.77	0.08	0.33	0.18	1.15	1.23	1.62	2.77	5.10	2.33	0.22	0.60	0.07	0.97	MgO
K_2O	1.95	2.06	1.02	1.08	1.31	0.78	1.65	1.07	1.67	3.75	5.28	4.42	1.37	0.55	1.63	0.82	1.19	0.88	4.15	4.24	1.22	1.03	K_2O
Na_2O	3.45	3.60	3.58	3.66	4.09	3.01	4.16	3.70	3.71	3.16	1.04	1.88	1.54	1.44	3.71	3.87	4.23	1.00	2.81	1.38	2.49	1.19	Na_2O
P_2O_5	0.182	0.108	0.201	0.220	0.228	0.371	0.135	0.156	0.202	0.107	0.041	0.023	0.011	0.127	0.590	0.511	0.800	0.035	0.201	0.034	0.020	0.220	P_2O_5
Total	96.19	97.67	99.38	99.06	100.12	98.60	99.01	99.60	99.50	98.55	96.07	93.30	96.12	92.29	97.75	97.74	99.11	93.32	97.16	91.65	89.86	87.64	Total
trace elements																							**trace elements**
Ni ppm	1.	11.	174.	188.	14.	149.	11.	71.	24.	10.	13.	12.	12.	20.	3.	9.	24.	19.	12.	12.	10.	10.	Ni ppm
Cr	4.	0.	264.	265.	25.	427.	26.	169.	77.	7.	11.	0.	1.	40.	7.	21.	34.	1.	11.	6.	0.	5.	Cr
Sc	7.	5.	22.	16.	13.	25.	14.	30.	22.	5.	8.	4.	2.	17.	31.	37.	25.	0.	12.	6.	6.	6.	Sc
V	1.	19.	142.	147.	137.	208.	86.	180.	149.	46.	30.	13.	0.	209.	98.	199.	217.	47.	37.	0.	18.	37.	V
Ba	526.	550.	363.	360.	394.	396.	535.	276.	392.	1089.	1210.	1030.	364.	294.	598.	455.	254.	1779.	932.	1787.	†3940.	923.	Ba
Rb	49.	54.	22.	25.	30.	24.	48.	25.	58.	87.	19.	118.	47.	37.	82.	60.	16.	15.	131.	90.	26.	32.	Rb
Sr	422.	34.	591.	620.	475.	578.	425.	477.	298.	206.	651.	309.	180.	409.	184.	195.	435.	188.	97.	614.	†1174.	453.	Sr
Zr	155.	151.	126.	133.	150.	151.	134.	116.	158.	136.	194.	213.	58.	293.	244.	233.	277.	297.	327.	219.	275.	152.	Zr
Y	12.	11.	13.	3.	17.	21.	11.	15.	25.	12.	†53	34.	13.	31.	†57	†53	37.	90.	†69.	†75.	†50.	†65.	Y
Nb	11.	10.2	10.	10.2	11.9	23.7	10.4	6.9	11.7	7.1	19.	23.	8.3	26.4	24.8	23.5	†35.4	†34.8	27.9	27.3	17.1	20.	Nb
Ga	19.	11.	18.	17.	21.	17.	20.	19.	20.	10.	23.	15.	12.	21.	26.	24.	26.	†30.	23.	24.	18.	17.	Ga
Th	6.	4.	3.	2.	3.	4.	6.	4.	5.	6.	11.	11.	5.	8.	8.	6.	2.	20.	13.	13.	16.	14.	Th
Mode(volume%)[2]																							**Mode(volume%)[2]**
phenocrysts/size	1-3 mm	0.2-3 mm	0.5-1 mm	0.5-1 mm	0.3-2mm	0.5-2 mm	1-2.5 mm	0.1-0.5 mm	1-2 mm	<0.5 mm	<0.5 mm	<2 mm	<1 mm	<2 mm	0.1-0.2 mm	0.1-0.2 mm	...	<1 mm	2-0.5 mm	<0.5 mm	<1 mm	<0.5 mm	phenocrysts/size
plagioclase (An%)	7.9 (An_{17-31})		4.6 ($An_{\sim10}$)	...	1.3 ($An_{\sim30}$)	11.3 (An_{16-54})	2.0 (An_{52-76})		8.0 (An_{25-26})	...	5.1(An_{39-56})	<1	<1	<25	<25	<5	0.3 (An_{22-52})	3.1 (An_{31-54})	...	<25	0.2 ($An_{\sim30-67}$)		<5 <5
<5plagioclase (An%)																							
sanidine	...	...	...	...	...	...	...	...	...	<1	<1	<25	<25	<5	...	...	...	<25	1.2	<5	<5	<5	sanidine
olivine	...	...	...	...	...	6.3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	olivine
clinopyroxene	...	...	0.1	...	...	...	0.1	0.9	0.1	...	...	...	...	...	0.1	0.2	...	...	...	...	...	...	clinopyroxene
orthopyroxene	...	...	...	...	1.5	...	...	...	...	...	...	...	...	...	...	0.1	...	...	...	...	...	...	orthopyroxene
hornblende	1.6	0.9	2.3	6.1	1.1	...	2.6	3.2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	hornblende
Fe-Ti oxides	0.4	0.1	...	...	0.1	0.1	0.3	0.1	1.9	<0.5	...	...	...	<1	...	...	...	...	...	...	...	...	Fe-Ti oxides
quartz	...	...	...	...	...	...	...	...	...	<1	<1	<25	<25	...	...	...	...	<25	4.3	<5	<5	<5	quartz
groundmass	...	94.4	...	87.9	...	...	...	...	...	...	...	...	...	...	...	...	0.1-2 mm	...	...	...	...	...	groundmass
plagioclase	...	...	63.7	...	51.1	38.2	...	55.6	41.1	...	...	...	...	...	...	...	63.2 (An_{10-65})	...	...	...	...	...	plagioclase
olivine	...	...	...	...	...	4.9	...	...	...	...	...	...	...	...	...	...	10.9	...	...	...	...	...	olivine
clinopyroxene	...	...	24.2	...	23.6	20.3	...	25.9	19.6	...	...	...	...	...	...	...	13.4	...	...	...	...	...	clinopyroxene
orthopyroxene	...	...	4.9	...	...	...	...	7.3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	orthopyroxene
apatite	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.8	...	...	...	...	...	apatite
Fe-Ti oxides	...	...	2.9	4.4	6.5	8.7	...	6.0	7.6	...	...	...	...	...	...	...	11.7	...	...	...	...	<1	Fe-Ti oxides
cryptocrystalline	90.1	...	...	...	...	...	89.0	...	...	...	...	...	...	...	99.6	95.5	...	~70	86.4	...	...	...	cryptocrystalline
glass	...	...	...	...	...	15.6	...	...	...	...	~48	...	...	...	...	...	...	...	...	...	~45	...	glass
alteration	...	...	1.9	0.3	5.5	3.9	...	1.0	24.0	~99	~48	~60	>75	~90	...	...	...	...	...	~85	~45	~70	alteration
clots	...	...	...	...	...	...	...	...	0.6	...	...	...	...	...	...	1.1	...	...	...	...	...	...	clots
pumice	...	...	...	...	...	...	...	...	...	...	1-2	<5	...	...	...	...	...	~1	4.5	<10	...	<15	pumice
lithic clasts	...	...	...	...	...	...	...	...	...	...	<1	<30	<1	<5	...	...	...	~1	3.4	<1	<1	<5	lithic clasts

[1] XRF analyses at GeoAnalytical Lab, Washington State University, Pullman, WA. "†" denotes values >120% of highest standard.

[2] 1000 points counted at 312.5x. Tuffs #10-14 and #18, 20-23 show estimated mode. Here feldspar is represented by both plagioclase and sanidine, and ferromagnesian minerals by Fe-Ti oxides.

Table 3. Descriptive petrography of analyzed samples

1. PHA93602. Phyric hornblende-plagioclase dacite of Hancock dome. Collected at 44o55′28″N, 120o25′35″W, UTM N 49977340, UTM E 703095, at 1790 ft elevation, Clarno 7.5′ quadrangle. Light-gray, randomly oriented phenocrysts of zoned plagioclase prisms, partly altered to sericite and calcite, and lesser elongated pale-brown hornblende prisms largely replaced by calcite, hematite, and a brown mineraloid (smectite?), and stubby prismatic opaques in a finely stipulated cryptofelsic groundmass.

2. PHA93611.Weathered phyric hornblende-plagioclase dacite boulder-size clast in comglomerate of "Hancock Canyon." Collected at 44o55′20″N, 120o25′44″W, UTM N 4977340, UTM E 702910, at 1690 ft elevation, Clarno 7.5′ quadrangle. Pale-brown, random phenocrysts of plagioclase prisms, mostly altered to brown mineraloids (smectite?), and hornblende prisms replaced by fine-grained opaques and brown mineraloid, in a very fine-grained felty groundmass of plagioclase microlites, opaques, and irregular masses of brown mineraloid and hematite.

3. PHA93603. Phyric hornblende andesite of Pine Creek, west lobe. Collected at 44o54′40″N, 120o26′09″W, UTM N 4976098, UTM E 702420, at 1385 ft elevation, Clarno 7.5′ quadrangle. Dark greenish-gray, random phenocrysts of hornblende, largely replaced by a brownish-green mineraloid (smectite?) rimmed with granular orthopyroxene and clinopyroxene, in a pilotaxitic groundmass of abundant plagioclase microlites, and intergranular pyroxene, opaques, and hematite.

4. PHA91618. Phyric plagioclase-hornblende andesite of Pine Creek, east lobe. Collected at 44o54′40″N, 120o25′12″W, UTM N 4976115, UTM E 703545, at 1470 ft elevation, Clarno 7.5′ quadrangle. Dark greenish-gray, random phenocrysts of hornblende, largely replaced by a brownish green mineraloid (smectite?), hematite , opaques, and rimmed with granular orthopyroxene, and lesser plagioclase prisms in a compressed swirly groundmass of plagioclase microlites and intergranular pyroxene, opaques, hematite, and brown mineraloid.

5. PHA93631. Phyric orthopyroxene-hornblende-plagioclase andesite, of middle andesite, in the west face cliffs. Collected at 44o53′17″N, 120o25′57″W, UTM N 4973500, UTM E 702765 at 1840 ft elevation, Clarno 7.5′ quadrangle. Dark-gray, random phenocrysts of well-zoned plagioclase prisms with patchy interiors, hornblende prisms replaced by orthopyroxene, granular opaques, brown mineraloid (smectite?), some clinopyroxene, with crowded rims of orthopyroxene, and zoned orthopyroxene, in a random to locally subparallel felty groundmass of plagioclase laths and intergranular pyroxene, opaques, and brown mineraloid.

6. PHA91613. Phyric plagioclase-olivine mafic (basaltic) andesite, amydaloidal "basalt" of conglomerate of "Hancock Canyon," Clarno Formation. Collected at 44o53′17″N, 120o25′32″W, UTM N 4977635, UTM E 703190, at 1900 ft elevation, Clarno 7.5′ quadrangle. Dark-gray, random phenocrysts of olivine with opaque inclusions, partly altered to iddingsite and iron oxide, and lesser plagioclase in a subaligned groundmass of abundant plagioclase laths, intergranular clinopyroxene, olivine, opaques, brown glass, a little calcite, and brown and green mineraloids (smectite?).

7. PHA91602. Phyric orthopyroxene-hornblende-plagioclase andesite, of upper andesite of Horse Mountain, Clarno Formation. Collected at 44o55′23″N, 120o24′58″W, UTM N 4977465, UTM E 704015, at 1920 ft elevation, Clarno 7.5′ quadrangle. Greenish-gray, aligned but randomly oriented phenocrysts of patchy zoned plagioclase, hornblende largely replaced by a pleochroic brown mineraloid resembling biotite (smectite?), granular opaques, and pyroxene in an indistinguishable pilotaxitic groundmass of plagioclase laths, altered acicular hornblende,

brown mineraloid, hematite, and granular opaques. Plagioclase forms a few scattered glomerophenocrysts 2.5-8 mm in size.

8. PHA93634. Sparsely phyric orthopyroxene-hornblende andesite of Horse Mountain, in west face cliffs, Clarno Formation. Collected at 44o53′27″N, 120o25′39″W, UTM N 4973805, UTM E 703155, at 2120 ft elevation, Clarno 7.5′ quadrangle.Gray, random phenocrysts of hornblende largely replaced by brown mineraloid (smectite?) and hematite, with crowded margins of granular orthopyroxene and lesser anhedral clinopyroxene, in a pilotaxitic groundmass of abundant plagioclase laths and intergranular pyroxene, opaques, and brown mineraloid.

9. PHA91609. Phyric plagioclase andesite, upper andesite of Horse Mountain, Clarno Formation. Collected at 44o55′49″N, 120o24′47″W, UTM N 4977530, UTM E 704045, at 2070 ft elevation, Clarno 7.5′ quadrangle. Gray, random phenocrysts of a few glomerophenocrysts of zoned plagioclase with patchy interiors, partly replaced by brown mineraloid (smectite?), lesser clinopyroxene, and clots of poikilitic opaques with hematite, in a pilotaxitic groundmass of abundant plagioclase laths and intergranular clinopyroxene, opaques, and brown mineraloid.

10. PHA93612. White tuff at fern-leaf fossil locality, in conglomerate of "Hancock Canyon," Clarno Formation. Collected at 44o55′27″N, 120o25′03″W, UTM N 4977528, UTM E 703705, at 1820 ft elevation, 3 m thick, Clarno 7.5′ quadrangle.Whitish very fine-grained clayey tuff, containing few crystals of probable quartz and feldspar, very sparse ferromagnesian minerals, with trace of limonite stain along fractures; thinly bedded, near laminar with undulations and fine-scale cross bedding.

11. PHA93644. Tuff of Currant Creek, below the Gable, Clarno Formation. Collected at 44o54′26″N, 120o27′40″W, UTM N 4975543, UTM E 700435, at 1320 ft elevation, 4-6 m thick, Clarno 7.5′ quadrangle. Very pale-gray very fine-grained clayey welded tuff, with sparse crystals of probable quartz and feldspar, rounded lithic grains, flattened white micropumice, and carbon, in a eutaxitically flattened matrix of glass and clay.

12. PHA94603. Tuff of Currant Creek at type locality, Clarno Formation. Collected at 44o49′24″N, 120o33′21″W, UTM N 4966015, UTM E 693225, at 1995 ft elevation, ~60 m thick, Arrastra Butte 7.5′ quadrangle. Pale pinkish-gray clayey pumice-lithic-crystal tuff, containing about 25% crystals of quartz and feldpar, 30% black to gray angular very fine-grained lithic fragments, a few rounded pumice lapilli altered to clay, and pink zeolite(?), in a clay matrix.

13. PHA93609. White tuff below the "Nut Beds," in conglomerate of "Hancock Canyon," Clarno Formation. Collected at 44o52′20″N, 120o25′49″W, UTM N 4977320, UTM E 702805, at 1850 ft elevation, 0.15 thick, Clarno 7.5′ quadrangle. Pale grayish-white silty-clayey tuff, containing about 25% subrounded, very fine-grained crystals of probable quartz and feldspar, and 1% lithic grains and carbon, in a clay matrix.

14. PHA93653. Tuff in claystone of "Red Hill," Clarno Formation. Collected at 44o55′23″N, 120o25′51″W, UTM N 4977423, UTM E 702762, at 1805 ft elevation, 2 m thick, Clarno 7.5′ quadrangle. Pale grayish-white sandy clayey crystal tuff, containing about 5% euhedral crystals of quartz and feldspar, 1% ferromagnesian minerals, chiefly magnetite, about 5% grayish rounded lithic fragments, some containing both feldspar and ferromagnesian minerals, 1% carbon, and about 5% brownish zeolite, in a clay matrix.

15. PHA91607. Sparsely microphyric clinopyroxene-plagioclase andesite in Member B, John Day Formation. Collected at 44o56′17″N, 120o24′17″W, UTM N 4979140, UTM E 704780, at 2290 ft elevation, Clarno 7.5′ quadran-

gle. Dark-gray, scattered aligned microphenocrysts of plagioclase and clinopyroxene in a subaligned hyalopilitic matrix of very fine-grained plagioclase microlites and interstitial granular pyroxene, opaques, and brown glass.

16. PHA93614. Sparsely microphyric pyroxene-plagioclase andesite dike; intrudes conglomerate of "Hancock Canyon," and apparently supplied andesite in Member B, John Day Formation. Collected at 44o55′52″N, 120o24′35″W, UTM N 4978364, UTM E 704536, at 1960 ft elevation, Clarno 7.5′ quadrangle. Dark-gray, scattered subparallel microphenocrysts of plagioclase laths and pyroxene prisms in a finely stipulated hyalopilitic matrix of subaligned plagioclase microlites and interstitial pyroxene, opaques, and brown glass.

17. PHA93651. Finely crystalline olivine trachybasalt of Member F, John Day Formation. Collected at 44o56′14″N, 120o25′41″W, UTM N 4978985, UTM E 702940, at 2080 ft elevation, Clarno 7.5′ quadrangle. Dark-gray, fine-grained radiating clusters of subhedral, well-zoned plagioclase laths with subophitic brown clinopyroxene, intergranular olivine, abundant subhedral opaques, and scattered apatite needles.

18. PHA94055. White tuff at base of Member A, John Day Formation. Collected at 44o55′14″N, 120o27′10″W, UTM N 4976380, UTM E 701070, at 1640 ft elevation, 4 m thick, Clarno 7.5′ quadrangle. Yellowish-gray clayey-sandy crystal tuff, containing about 25% crystals of probable quartz and feldspar, 1% micropumice, 1% lithic grains, in a clay and zeolite matrix.

19. PHA94057. Welded pumice-crystal (feldspar-quartz) vitric tuff, Member A, John Day Formation. Collected at 44o55′14″N, 120o27′10″W, UTM N 4976380, UTM E 701070, at 1640 ft elevation, 15 m thick, Clarno 7.5′ quadrangle. Pale orange,scattered euhedral to anhedral crystals of plagioclase, sanidine, and quartz, in a devitrified eutaxitically compressed matrix of indistinguishable very fine-grained crystals of probably feldspar and quartz with abundant hematite and limonite, spherulites, a few flattened pumice lapilli and rounded lithic grains, and minor calcite and clay. [Examination under binocular microscope: Light olive-gray well-compressed tuff, containing about 10% euhedral quartz and feldspar, and about 10% pinkish-gray flattened pumice lapilli, in a matrix largely devitrified to very fine-grained crystals, clay, and zeolite.]

20. PHA93615. White tuff in upper part, Member A, John Day Formation. Collected at 44o56′09″N, 120o24′13″W, UTM N 4978910, UTM E 704865, at 2270 ft elevation, 6-8 m thick, Clarno 7.5′ quadrangle. Pale pinkish-white silty-clayey tuff, containing less than 5% very fine-grained probable quartz and feldspar, less than 10% white rounded micropumice altered to clay, and less than 1% lithic particles, in a clay matrix; well bedded and compacted.

21. PHA95610. White tuff of Member F, John Day Formation. Collected at 46o56′15″N, 120o24′59″W, UTM N 4979062, UTM E 703803, at 2200 ft elevation, 2-3 m thick, Clarno 7.5′ quadrangle. Very pale yellow-gray fine-grained clayey tuff, containing about 5% euhedral crystals of probable quartz and feldspar, less than 1% rounded lithic grains, in a vitric and clay matrix.

22. PHA95605. White tuff in middle Big Basin Member, John Day Formation. Collected at 44o56′57″N, 120o23′40″W, UTM N 4980395, UTM E 705570, at 2520 ft elevation, 0.7 m thick, Clarno 7.5′ quadrangle.Very pale yellowish-gray very fine-grained clayey tuff, containing less than 5% crystals of probable quartz and feldspar, 15% micropumice, 5% rounded lithic grains, and spots of hematite, in a clay matrix.

[23.PHA88601. Welded pumice-crystal (sanidine-quartz-plagioclase) vitric tuff, Member A, John Day Formation. Collected at 44o55’32”N, 120o25’28”W, UTM N 4977675, UTM E 703280, at 1880 ft elevation, 6-8 m thick, Clarno 7.5’ quadrangle. Light-gray eutaxitically layered, welded pumice-lapilli tuff, containing scattered random prismatic crystals of sanidine, embayed quartz, and plagioclase in an indistinguishable compressed cryptofelsic, spherultic matrix containing “ghosts” of pumice, and opaques, limonite, and hematite.]

APPENDIX

Age determinations for some Clarno Formation rocks, summary table and graphic representations.

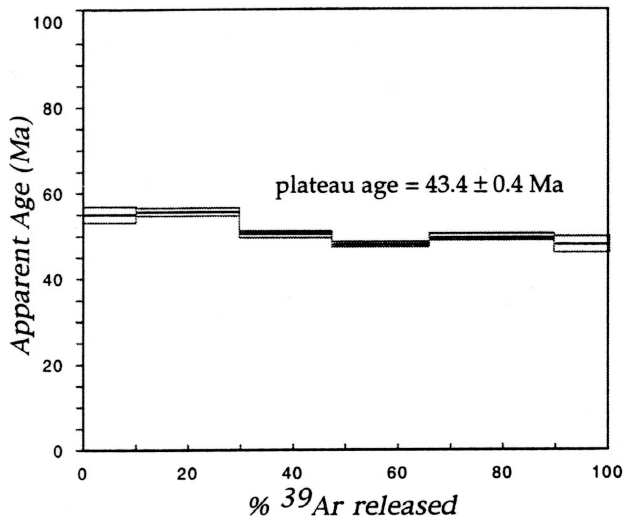
By Robert A. Duncan, Oregon State University.

Table 4: ^{40}Ar-^{39}Ar Incremental Heating Ages for Rocks from the Clarno Formation, Eastern Oregon

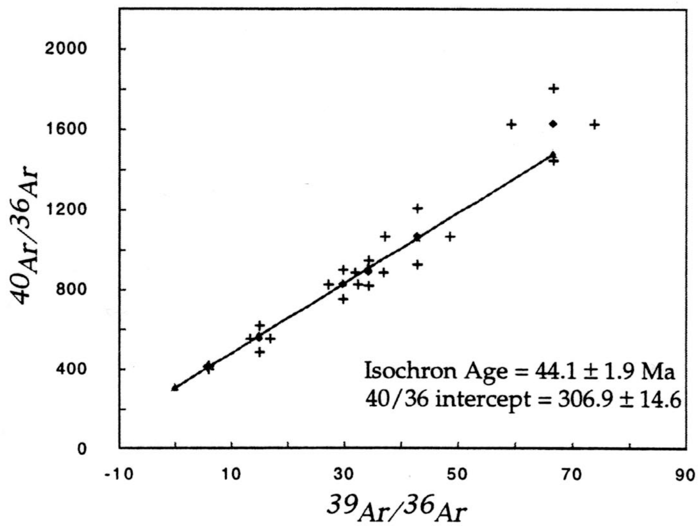
Sample Number	Material	Total Fusion Age (Ma)	Plateau Age (Ma)	^{39}Ar % of Total	Isochron Age (Ma)	N	$^{40}Ar/^{36}Ar$ Intercept ± 1σ	J
93634	andesite (plagioclase)	45.1	43.4 ± 0.4	70.3	44.1 ± 1.9	6	306.9 ± 14.6	0.001658
93653	tuff (plagioclase)	43.0	42.7 ± 0.3	91.6	43.7 ± 0.6	5	289.8 ± 5.8	0.001403
91613	basalt (plagioclase)	43.2	43.8 ± 0.5	74.3	45.2 ± 8.1	5	217.4 ± 264.9	0.001349
93603	andesite (whole rock)	50.8	51.2 ± 0.5	62.4	48.3 ± 4.4	6	233.6 ± 339.2	0.001555
93602	dacite (plagioclase)	57.2	53.6 ± 0.3	44.4	56.1 ± 0.6	5	289.8 ± 2.2	0.001680

Ages are reported relative to biotite monitor FCT-3 (28.04 ± 0.12 Ma), which is calibrated against hornblende Mmhb-1 (523.5 Ma, Renne et al., 1994). Plateau ages are the mean of concordant step ages (N = number of steps), weighted by the inverse of their variances. Calculations use the following decay and reactor interference constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}\ yr^{-1}$, $\lambda_\beta = 4.963 \times 10^{-10}\ yr^{-1}$; $(^{36}Ar/^{37}Ar)_{Ca} = 0.000264$, $(^{39}Ar/^{37}Ar)_{Ca} = 0.000673$, $(^{40}Ar/^{39}Ar)_{Ca} = 0.01$. J is the neutron fluence factor, determined from measured monitor $^{40}Ar/^{39}Ar$.

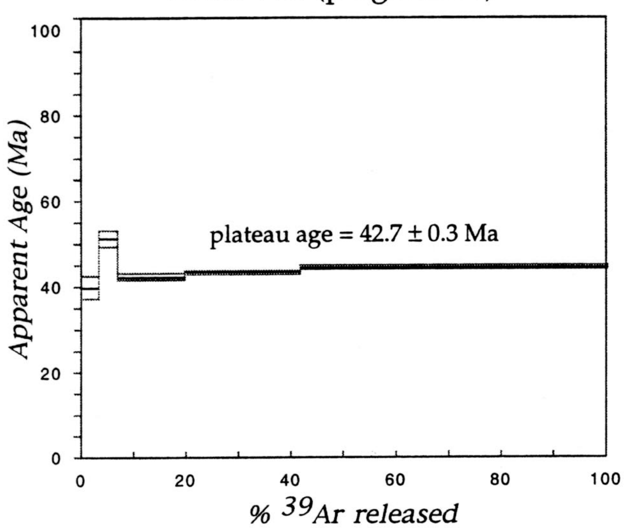
93634 andesite (plagioclase)



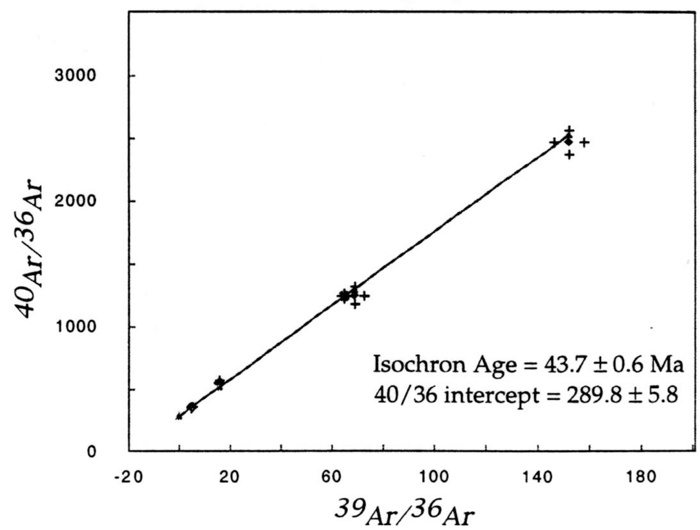
93634 andesite (plagioclase)



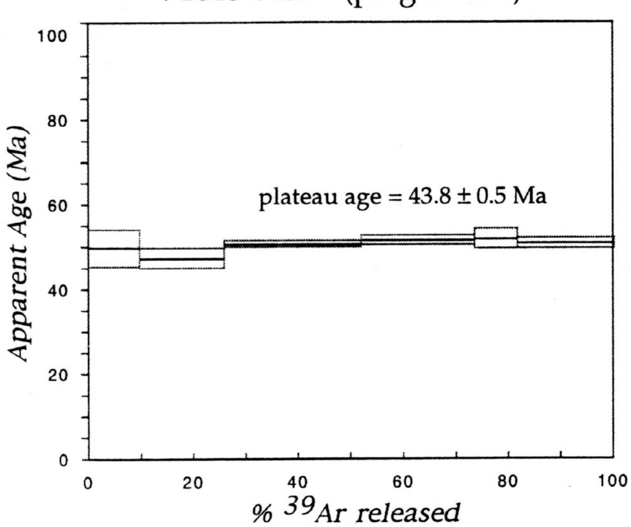
93653 tuff (plagioclase)



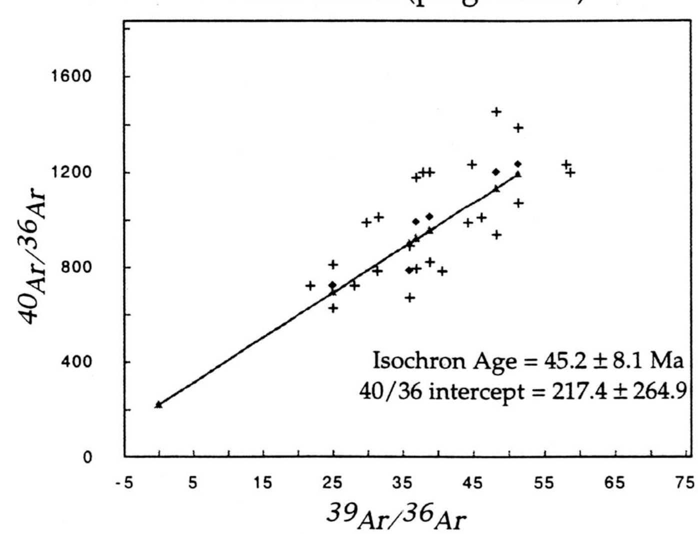
93653 tuff (plagioclase)

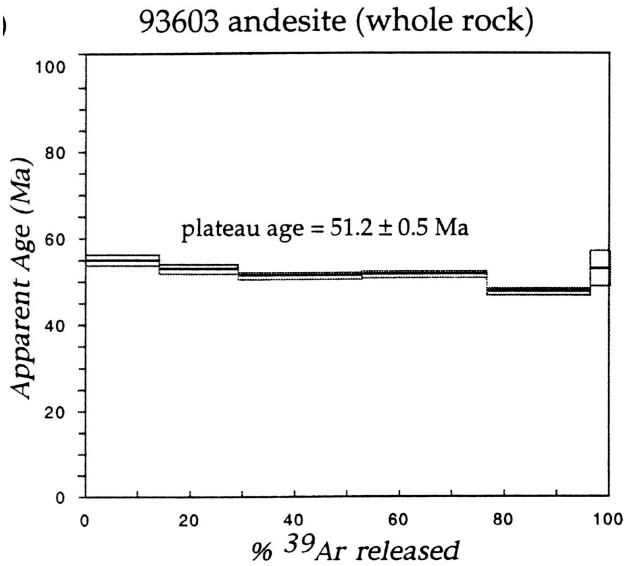


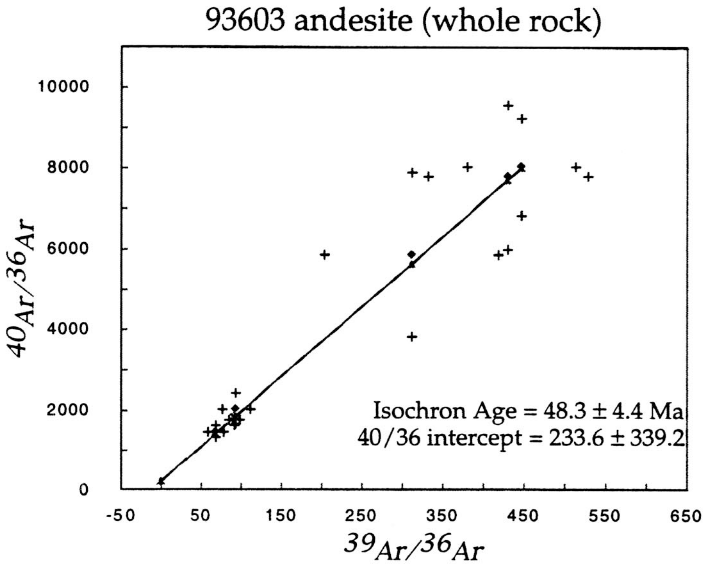
91613 basalt (plagioclase)

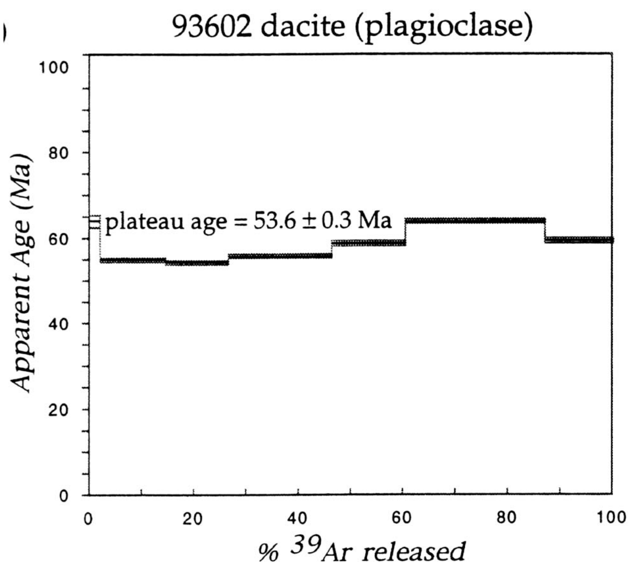


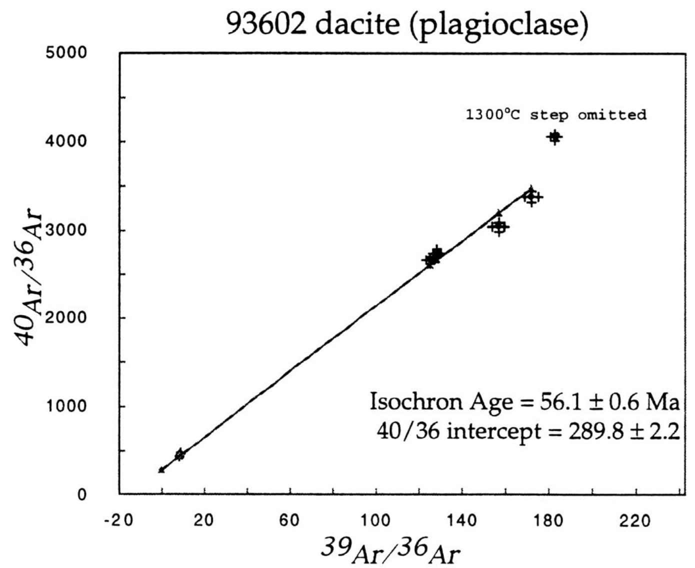
91613 basalt (plagioclase)




93603 andesite (whole rock)
Apparent Age (Ma)
plateau age = 51.2 ± 0.5 Ma
% 39Ar released
0
20
40
60
80
100


93603 andesite (whole rock)
40Ar/36Ar
Isochron Age = 48.3 ± 4.4 Ma
40/36 intercept = 233.6 ± 339.2
39Ar/36Ar
-50
50
150
250
350
450
550
650
0
2000
4000
6000
8000
10000


93602 dacite (plagioclase)
Apparent Age (Ma)
plateau age = 53.6 ± 0.3 Ma
% 39Ar released
0
20
40
60
80
100


93602 dacite (plagioclase)
40Ar/36Ar
1300°C step omitted
Isochron Age = 56.1 ± 0.6 Ma
40/36 intercept = 289.8 ± 2.2
39Ar/36Ar
-20
20
60
100
140
180
220
0
1000
2000
3000
4000
5000

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